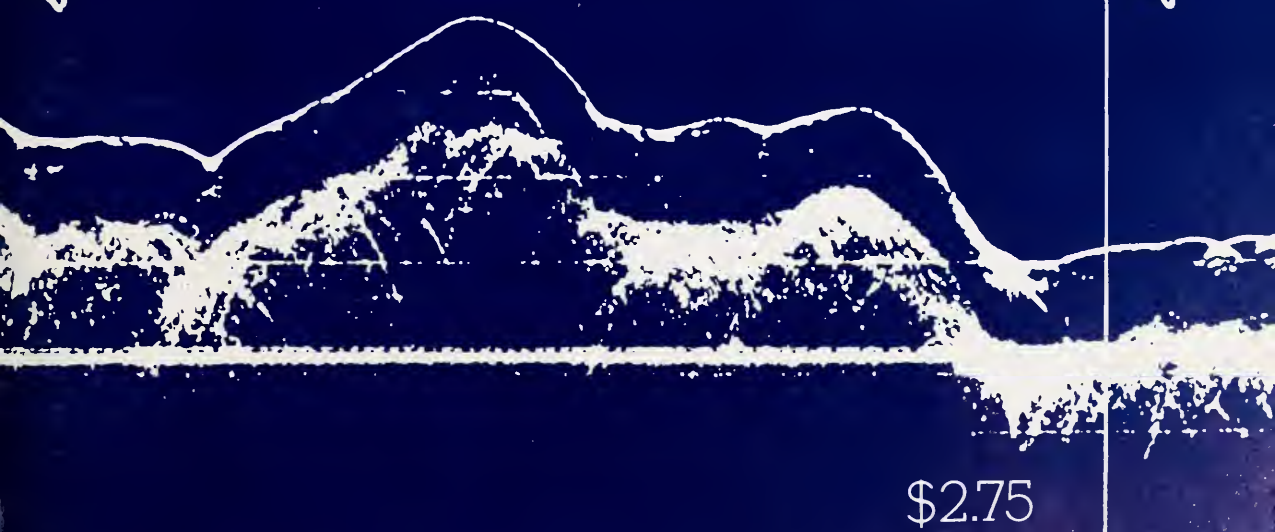
Oceanus

Volume 20, Number 1, Winter 1977

HIGH-LEVEL NUCLEAR WASTES IN THE SEABED?



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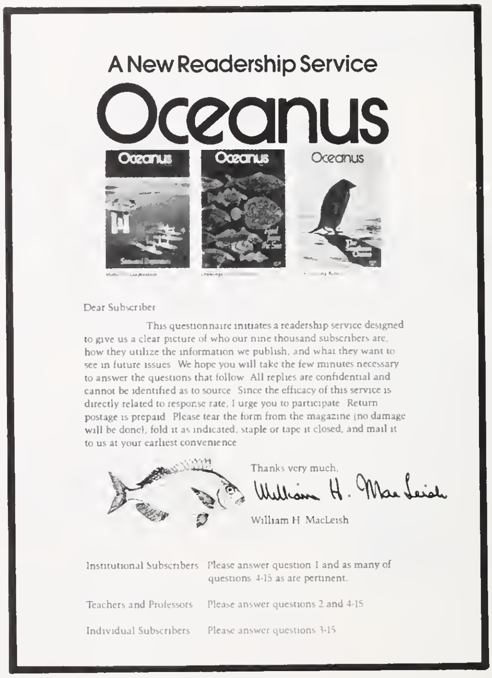
Reader Reaction

The summer, 1976, issue carried a four-page questionnaire asking readers to give us their preferences and criticisms. The response — 780 returns, or 8.6% — was heartening and instructive, a good sampling of those who react most strongly to the magazine. Several respondents asked to see the results. Here are some we found of particular interest:

- *Almost half of all returns carried commentary (question 15). There were a few brickbats, but most were complimentary. The blithest came from a research coordinator overseas: "Keep on truckin'!"*
- *The educational field carried the day in numbers and enthusiasm, followed by business and government. More than half of total responses came from researchers, professors, high-school teachers, and from students at levels ranging from graduate to secondary.*
- *More than half — 53% — of the respondents rated marine science as a high-priority area. An additional 28% gave it first priority.*
- *The most populous age class among respondents was 25-34 (34%), followed by 35-49 (22%) and 50-64 (19%).*
- *Only 4% found the magazine too technical, while 29% said they were sometimes stumped, and 67% said they had no problems on that score.*
- *On frequency, 59% answering that question said they wanted six or more issues a year. The rest liked the quarterly approach.*
- *Three questions dealt with editorial mix. Most respondents answering them felt the current ratio of three thematics to one general issue was most desirable (59%), though 31% would prefer an even split. A third rated oceanographic research as the subject area they wanted stressed; 23% preferred environmental matters, and 22% marine resources. Reviews of books in pertinent fields was the most strongly favored among suggested editorial departments, followed by reports on oceanographic cruises (25%) and a calendar of important events in marine science (21%).*
- *Three-quarters of the respondents said they kept* Oceanus *for reference. Half gave or lent their copies to other readers or to libraries.*

So. We have a lot to ponder. A response like this warms the cockles these late winter days, and we thank you. Any and all additional comments are always welcome.


A New Readership Service

Oceanus

Dear Subscriber

This questionnaire initiates a readership service designed to give us a clear picture of who our nine thousand subscribers are, how they utilize the information we publish, and what they want to see in future issues. We hope you will take the few minutes necessary to answer the questions that follow. All replies are confidential and cannot be identified as to source. Since the efficacy of this service is directly related to response rate, I urge you to participate. Return postage is prepaid. Please tear the form from the magazine (no damage will be done), fold it as indicated, staple or tape it closed, and mail it to us at your earliest convenience.

Thanks very much,

William H. MacLeish

William H. MacLeish

Institutional Subscribers	Please answer question 1 and as many of questions 4-15 as are pertinent.
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NOTICE TO SUBSCRIBERS

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Rising costs have forced us to raise prices for subscriptions entered or renewed after January first, 1977. The new domestic rates are $10 for one year, $18 for two. There will continue to be a $2 per year handling charge for foreign subscriptions.

Special Student Rate

As of January first, 1977, students at all levels can enter or renew subscriptions at the rate of $8 for one year, a saving of $2. This special rate is available only through application to: *Oceanus*, Woods Hole Oceanographic Institution, Woods Hole, Mass. 02543.

Attention Teachers

We offer a 40 percent discount on bulk orders of five or more copies of each current issue — that comes to only $1.65 a copy. The same discount applies to back copies ($1.80) and to one-year subscriptions for class adoption ($6 per subscription). Teachers' orders should be sent to our editorial office at the address listed above, accompanied by a check payable to Woods Hole Oceanographic Institution.

BURYING FAUST

Radioactive waste management. It has an efficient if ominous sound, evoking images of policy makers and technologists doing what is necessary to keep us tidily isolated from our nuclear residues. And on certain points image and reality aren't so far apart. Ever since United States weapons programs began generating radioactive garbage thirty-odd years ago, the safety record has been remarkable: some leakage, some mistakes in handling, but nothing that would stay long on the front page.

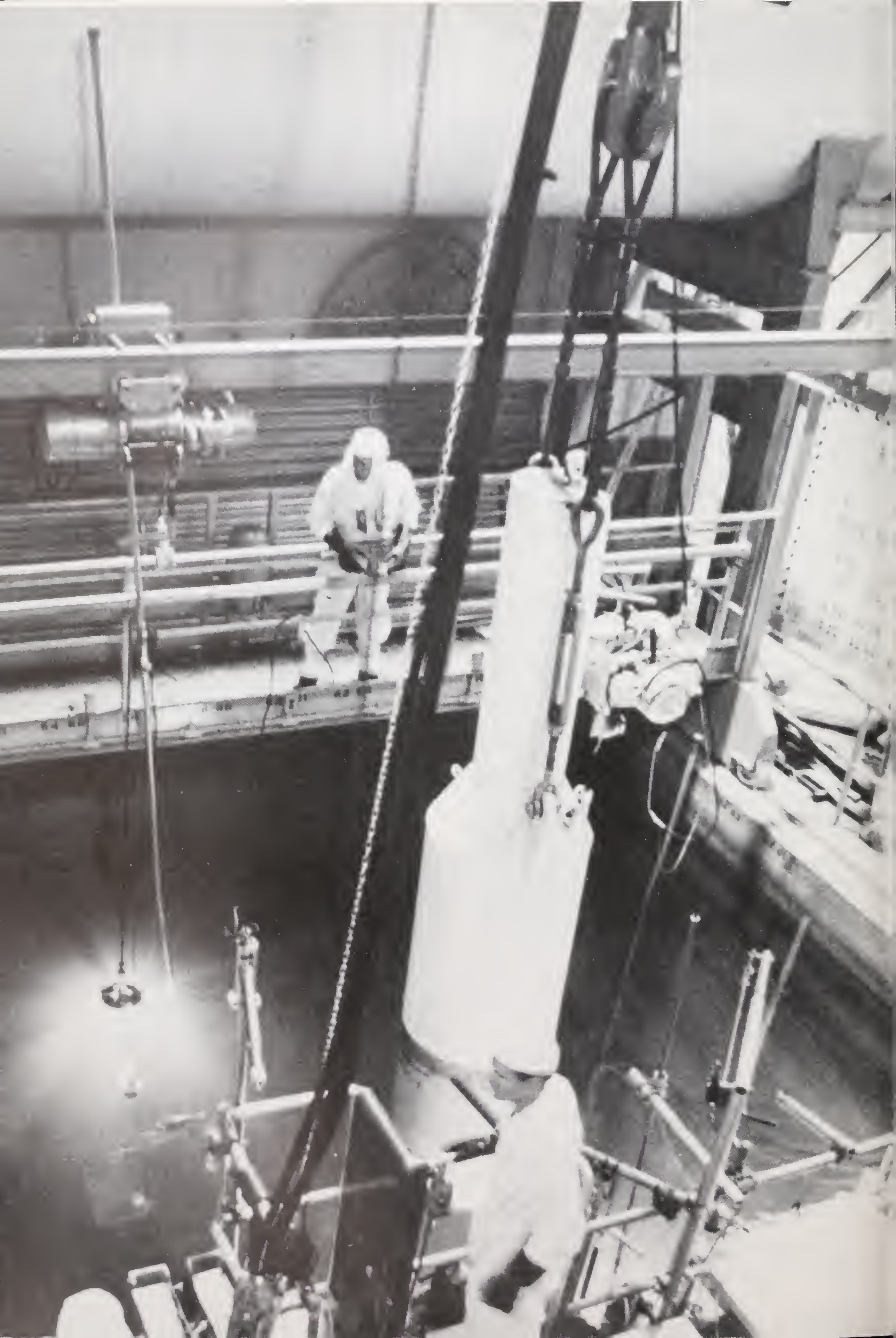
So far so good, you might say. But then, so might someone halfway through a long fall. What we have been doing by and large is to store our wastes on a temporary basis. We have not solved — indeed, despite urging from more than a few scientists, we have only recently begun to spend significant amounts of money on — the problem of permanent disposal. It is an ethically, politically, and technically difficult problem — an international issue of increasingly serious dimensions, stressed in no small way by the current drive to use nuclear power to reduce dependence on fossil fuels.

Of particular importance are the high-level radioactive wastes hazardous to life for more than a million years. They must be placed in repositories safe from geologic or human disturbance, isolated for thousands of centuries from the web of life. Where? The United States and several other nuclear powers are concentrating on terrestrial geologic formations — salt, shale, granite — and considerable data have been accumulated to support this focus. Yet here, as in so many other areas of social concern, there is disagreement among the experts. More importantly, perhaps, there is public opposition. Some opponents cite what they regard as the Faustian nature of the disposal bargain — present advantage in return for liability stretching millenia into the future. Others worry about accidents, about the effects of the repositories on industry or land values. There is an understandably strong not-in-my-backyard attitude.

Terrestrial disposal may prove feasible or it may not. The search for alternatives is on, some of it at sea. Several scientists have spent the past three years investigating the sub-seabed in certain deeps. They have examined the physical and chemical properties of the sediments, their geologic history, the biology of bottom communities. They do not now advocate emplacement of high-level radioactive wastes in those abyssal clays, but they have not encountered anything that would automatically rule out such disposal. Their work goes on. Some of it is presented in this issue, along with comments on the overall radioactive waste problem and the political aspects of the seabed option.

Disposal is imperative, but it is probably safe to say that time is still with us. In fact, haste at this point may force mistakes and heighten the hazard. After all, we have lived for some years in the age of the manufactured risk. We are surrounded by poisons of our own making, some extremely dangerous and long lived. We have not dealt with them well, witness our belated awakening to the threat of "environmentally caused" cancers. Perhaps radioactive waste, with its almost archetypal ability to inspire fear, can sharpen our sensing of reality.

William H. MacLeish



DISPOSING OF HIGH-LEVEL RADIOACTIVE WASTE

by Robert A. Frosch

One of the prime issues in deciding whether the United States and other countries should rely on nuclear power as a major energy source arises from the nature of the wastes produced in the commercial nuclear fuel cycle (Figure 1). High-level nuclear wastes are extremely toxic, with some fission product radionuclides having effective lifetimes of more than a million years.

While some think that this long-lived toxicity poses a unique problem, many substances in common use also have long toxic lifetimes. For example, arsenic and heavy metals, such as lead, are indefinitely toxic. Usually, we are not faced with having to dispose of large quantities of these materials, although we do find them in our dwellings and elsewhere in amounts that possibly could be fatal if swallowed or otherwise put into the human body. These poisons though do not pose a "hazard from mere proximity" as some radioactive materials do. Contact with lead, for example, is not dangerous, but even short contact with cesium 137 can be. We are only beginning to appreciate the dangers of these nonradioactive poisons.

As we delve into this problem, we should keep in mind that nearly all energy systems produce wastes in one form or another that pose a danger to man and his environment. We are thus faced with a complex system of trade-offs among various sources of energy that all carry some penalty for use. The comparison with other toxins and energy systems, however, does not change the problem created by dangerous commercial nuclear waste. This material must be stored or disposed of in a manner that will be safe from a human and environmental point of view.

Failure to provide convincing plans for the management of this waste resulted in a July 1976 decision by the U.S. Court of Appeals in the "Vermont Yankee" case. The court decision had the effect of barring the Nuclear Regulatory Commission (NRC) from licensing commercial nuclear power plants in the United States until the court is convinced that the NRC has adequately examined the question of disposition of waste.

In its decision, the court noted: "Once a series of reactors is operating, it is too late to consider whether the wastes they generate should have been produced, no matter how costly and impractical reprocessing and waste disposal turn out to be; all that remain are engineering details to make

A spent-fuel assembly from a nuclear reactor being lowered into a storage pool at the Pacific Gas and Electric's Humboldt Bay power plant near Eureka, Calif. (Courtesy ERDA)

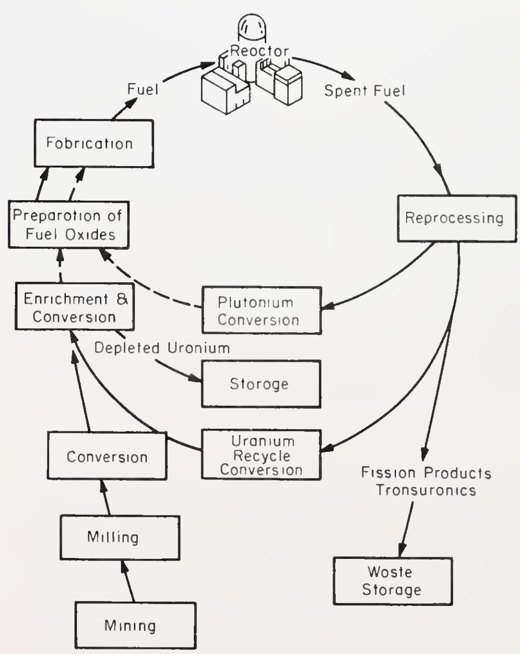


Figure 1. A typical commercial Light-Water Reactor fuel cycle that produces high-level radioactive wastes. No long-term management program has been implemented as yet for the disposal of these highly toxic materials. (Courtesy ERDA)

the best of the situation which has been created." It also commented that the decisions to license nuclear reactors were "a paradigm of irreversible and irretrievable commitments of resources" that must receive "detailed" analysis under the National Environmental Policy Act.

The United States is not alone in this problem. The question of inadequate waste management recently became a public issue in Britain after the Royal Commission on Environmental Pollution issued a report that stated: "There should be no commitment to a large programme of nuclear power until it has been demonstrated beyond reasonable doubt that a method exists to ensure the safe containment of long-lived highly radioactive waste for the indefinite future." Other countries, too, are closely examining this question.

The growing international awareness of the dangers inherent in commercial nuclear wastes undoubtedly has been influenced by the fact that, after 30 years of manufacturing plutonium for nuclear weapons, the United States has not firmly established management plans for the final disposal of millions of gallons of high-level wastes produced for military programs.

Estimates vary on the time when waste from commercial reactors in the United States would equal that produced in our weapons program. The precise time depends on the rate of expansion of commercial nuclear power and what happens in the future in regard to the production of weapons plutonium. The "crossover" dates also vary, depending on whether the estimate is based on the *volume* or the *activity* of waste. Reactors that produce plutonium for weapons yield wastes with lower radioactive intensities per unit volume than do commercial power reactors. The amount of a radioactive material is usually stated in curies (a curie is a quantity of radioactive material that undergoes 37 billion disintegrations per second, which is equivalent to the radiation intensity of 1 gram of radium).

Since shortly after the beginning of the nuclear era in 1942, the majority of military waste has been stored at government sites at Hanford in the state of Washington and at Savannah River, North Carolina. In addition, high-level wastes from nuclear-powered vessels have been kept at Idaho Falls, Idaho.

These waste materials are stored in several forms. At Hanford, 50 million curies of strontium 90 and cesium 137, the most intensely radioactive elements (many curies per gram) and those generating the most heat, have been separated out and are stored in heavy steel canisters in water pools. This represents about 80 to 90 percent of the strontium and cesium in the waste. The remaining materials — residual fission products, trivalent actinides, and a small amount of unextractable plutonium — are stored in large tanks as liquids, sludge, and sodium nitrate salt cake. The current inventory is about 75 million gallons of liquids, sludge, and salt cake. Of this amount, about 22 million gallons of liquid and 29.5 million gallons of salt and sludge are stored at Hanford (Figure 2). At Savannah River, about 25 million gallons of unseparated alkaline liquids, salt cake, and sludges are stored in double-walled steel tanks provided with cooling coils to remove the heat produced by the strontium and cesium.

The total amount of nuclear waste expected to be in storage at Hanford sometime after 1980 has been estimated to be 360 million curies. The total military waste at all sites in the United States during this period will probably be about 500 million curies, the exact amount depending upon details of future weapons production programs. According to the Energy Research and Development Administration (ERDA), the accumulated solidified high-level wastes from commercial Light-Water Reactors (LWRs) at a federal repository would reach 500 million curies between 1988 and 1999. This is based on an estimate of 254,000 megawatts installed LWR electrical capacity by 1988. Since this is two-thirds of the total nuclear capacity estimated to be installed by then, the crossover date on this estimate — when commercial wastes will exist in greater quantities than military wastes — comes somewhat earlier in the 1980s.

The failure to satisfactorily plan for the long-term disposal of military waste has led to skepticism in many quarters that the United States can manage the waste from civilian power reactors. While the fact that proper action was not taken in the past does not mean that it cannot be taken now, the history of past management leads to a perhaps justified lack of confidence that proper planning and management will be done, or can be done.

It should be noted, however, that no one has been harmed by our stored military wastes. In principle, they could, with care and vigilance, continue to be stored in tanks for a long time. There have been several leaks from the tanks, which have left radionuclides in the soil in the immediate vicinity. We must face the fact that no metal tank left in the open, or in shallow burial, can be expected to last without corrosion and related problems for hundreds of years. Thus, continued care, maintenance, and replacement of tanks is a

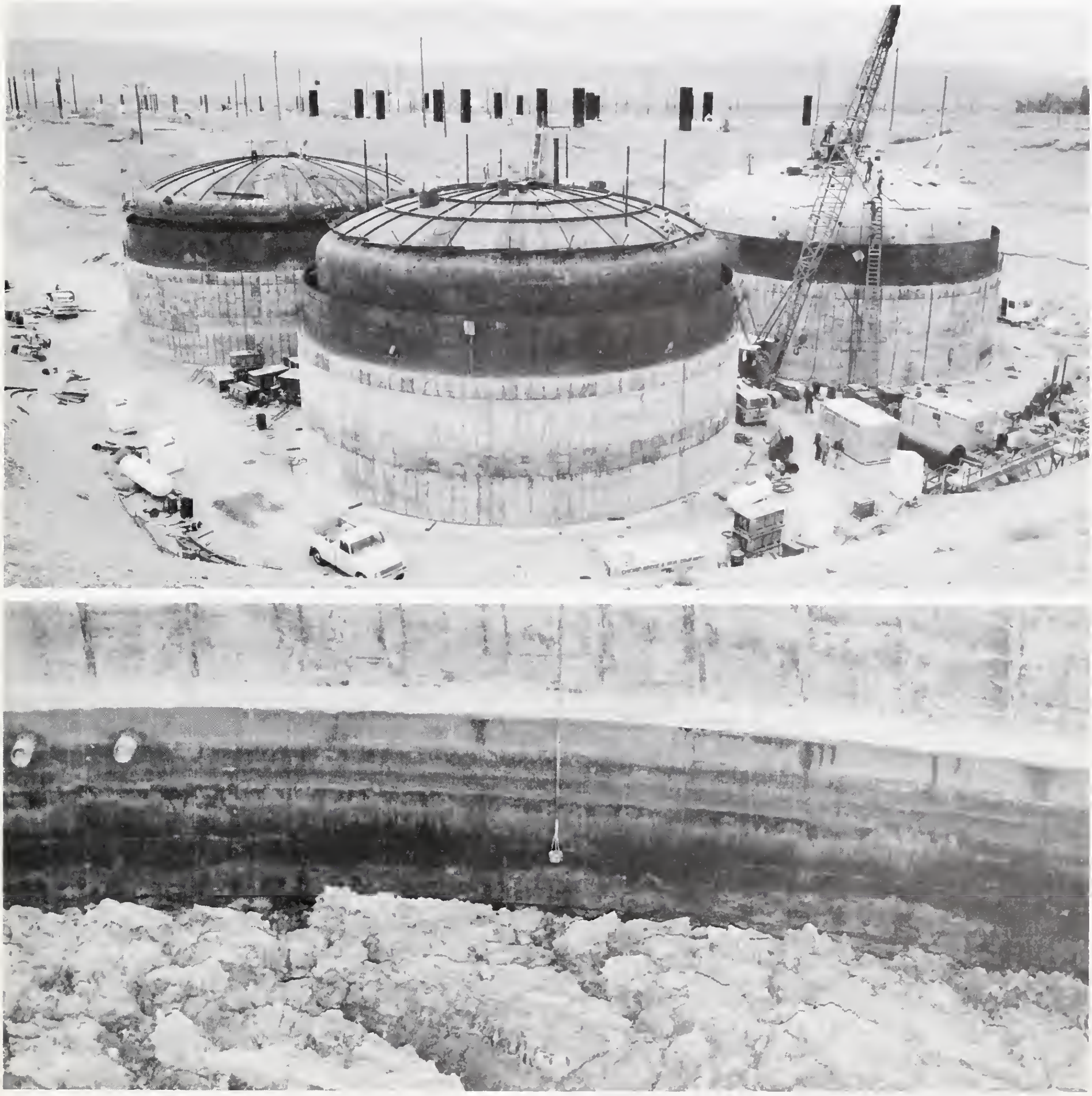


Figure 2. Above, three double shell, one-million-gallon capacity radioactive waste storage tanks under construction at the Energy Research and Development Administration's Hanford complex in the state of Washington. Below, liquid high-level radioactive wastes that have been converted into solid salt cake inside a Hanford storage tank. (Courtesy Battelle-Northwest)

necessity. Indefinite use of such a system poses a hazard to the workers involved and requires a commitment of almost endless human attention.

In any case, the very existence of the military high-level waste means that we already have a management problem that must be solved *whether or not* we commit ourselves to a major expansion of nuclear power.

The long-lived nature of the radioactive wastes (involving periods up to and beyond a million years) also raises a number of new questions about social responsibility. We are quite used to worrying about the effect of policy on ourselves, our children, and our grandchildren, but our concern gets more difficult to define and deal with when it extends beyond that stage. How are we to think about the problem of management of radioactive materials when the danger may last for times similar to the archeological history of man? Can we devise a management plan that will somehow continue to operate longer than any known human system, longer than some geological and climatological

times? Should we even try to do this? Or should we assume that generations to come will somehow improve upon the actions that we take?

Other major questions of social import arise, too. The largest is connected with the nonproliferation of nuclear weapons in which we all have a stake. In the commercial energy cycle spent nuclear fuel rods used to power reactors can be reprocessed to gain more fuel. In this process, plutonium, central to the manufacture of nuclear explosives, can be extracted. The further sale or dissemination of reprocessing technology thus could lead to a larger number of nations owning nuclear weapons. There is, of course, the possibility that these weapons could fall into the hands of terrorists. It has been suggested that the extra energy made available from these reprocessing units would not be worth the potential danger. The United States, in fact, has been trying to slow what many feel is the inevitable worldwide growth of these facilities with their attendant waste management problems.

It is in the context of these dilemmas that we must consider the technical, scientific, and social means for the management of nuclear waste.

The Origin of High-Level Wastes

When the nucleus of the uranium atom of atomic weight 235 is hit by a neutron, a subatomic particle, it will generally come apart — fission — into two fragments, each approximately half the original atomic weight. In addition to the two major fragments, there usually will be two or more neutrons emitted. In a reactor, these extra neutrons may hit nearby nuclei of uranium 235 and cause them in turn to undergo fission. Thus, an increasing number of uranium nuclei may undergo fission in a continuing and expanding chain reaction (Figure 3). Because more energy in the form of mass is stored in the uranium 235 nucleus than in the sum of the internal energies of the fission product nuclei, there is extra energy made available by the velocity of the fission fragments and the neutrons. The velocities of these nuclei produce heat. Thus, uranium 235 may participate in a self-sustaining reaction of fission that produces nuclei of lower atomic weight atoms in a heated state. In addition to their energy as particles, most of the fission fragments are nuclei that are themselves unstable and undergo radioactive decay, emitting several kinds of subnuclear particles and electromagnetic radiation (gamma rays).

Uranium 235 occurs in nature mixed as a minor constituent of natural uranium (the most abundant uranium isotope has an atomic weight of 238). In practice, reactor fuel is a mixture of uranium 235 and 238 that is packaged with other materials (for chemical and mechanical handling reasons) to make up fuel rods, which are installed into the "core" of a reactor.

When uranium 238 is struck by a neutron emitted in the fission of uranium 235, it undergoes a chain of radioactive decay into plutonium 239. Sequential captures of several neutrons by uranium 238 results in its transmutation into other radioactive transuranic elements (with atomic numbers higher

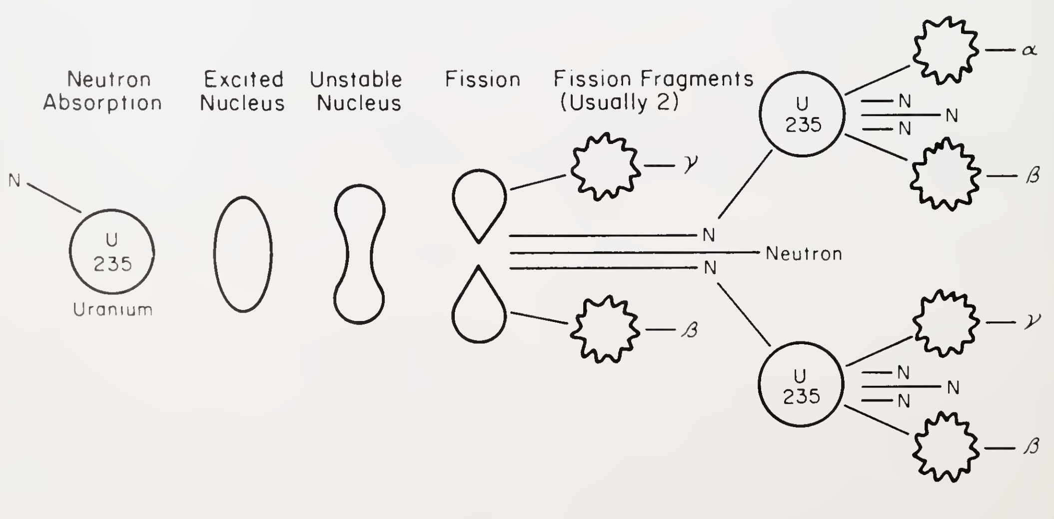


Figure 3. Fission of a nucleus of uranium 235 is induced by the absorption of a thermal, or slow, neutron (n), which excites the nucleus, causing it to change form and become unstable, eventually splitting into two fragments of unequal size. The fragments are themselves unstable and are transformed by their subsequent decay, so that the total spectrum of fission products includes many isotopes of more than 30 elements. At the moment of fission, gamma rays (γ) are emitted, as are a few neutrons. For a chain reaction to be sustained, at least one neutron must be absorbed and must induce fission in another nucleus of uranium 235.

than 92). The elements other than uranium present in the reactor container and core change into atomic species that are also radioactive when bombarded by the neutrons or by the gamma rays emitted in decay of the fission products.

In addition, the plutonium created by neutron capture in uranium 238 is itself subject to fission when bombarded by more neutrons, and it, too, contributes to the heat energy of the reactor, as well as to the buildup of radioactive fission products. Plutonium can be used as the basic fuel of a reactor in the same manner as uranium 235.

Thus, the energy from a reactor exists in the form of heat due to the motion of the nuclei remaining from the fission of the basic fuel, and in the form of the radioactivity of these nuclei. Also nuclei of plutonium and other heavy elements are produced, which themselves are radioactive, and some of which are also capable of fission. The heat produced by the fission process is absorbed by the water surrounding the core. This hot water may be used to produce steam, which, in turn, is used to generate power in a steam turbine.

The chain reaction of the fission process in the reactor is controlled by the insertion of materials (usually in the form of steel rods containing boron) that absorb neutrons and thus can regulate the amount of energy produced.

Three Basic Types of Reactors

There are three basic possible designs for reactors. The first is one that at peak efficiency produces heat, with plutonium a by-product (present commercial LWRs). The second is one designed to produce plutonium, with heat a by-product (military reactors used for weapons); and the third is a combination of the first two that will produce both plutonium and heat. This is known as a "breeder" reactor. These basic reactors can in turn be designed with different heat exchange materials (coolants) other than water. These include gases and liquid metals. The advantage of the breeder reactor is that by producing both heat (from the fission of uranium 235) and plutonium (from the transmutation of uranium 238) it provides power, while at the same time increasing the total amount of reactor fuel available over that available from using only natural uranium 235. A disadvantage is that highly purified plutonium can be made into nuclear explosives without the expensive and difficult physical separation processes necessary to get uranium 235 in a form pure enough to be used for fission weapons. As noted earlier, this gives rise to concern about the proliferation of nuclear weapons.

Other reactor systems, notably those based on the heavy element thorium, are possible. However, they will not be discussed because at the present time the most active planning is based on uranium and plutonium cycles.

Reprocessing

After the processes we have described to date have taken place in the core of a reactor of any design, the fuel then gradually changes its character, consisting more and more of fragments from the fission of uranium 235 or plutonium, and of transuranic elements. Thus, at a certain point, the effectiveness of the rod in producing energy begins to decrease, the fuel in the rod having been "burned," leaving many non-fissile elements present to interfere with new fission reactions. At this point, it is removed and replaced by a fresh fuel rod.

There are two basic possibilities for handling the spent fuel rods: they may be reprocessed so that the reusable uranium and plutonium can be extracted, or they may be discarded as waste (this is known as the "throwaway fuel cycle").

If the choice is to reprocess the spent fuel rods, uranium and plutonium will then be extracted and made into new fuel elements to be burned further in the fission process. Fuel elements may be made from uranium compounds only, plutonium compounds, or from a combination of the two (mixed-oxide fuel). The remaining materials — a mixture of fission products, generally highly radioactive, with some residual plutonium, uranium, and other transuranic elements — are the high-level wastes that must be dealt with in some manner.* In a "breeder" cycle, the plutonium from the spent fuel rod would be almost entirely separated out (99.5 percent) for further use as fuel; but, if it were decided not to use plutonium as a fuel, this material would be included in the waste faction.

The Nature of the Waste

Most of the materials in the waste are radioactive. Radioactive elements are described in terms of their

**There are other types of radioactive waste that arise from the nuclear fuel cycle. These include the materials of the reactor itself that may have to be changed in the course of maintenance or repair, and that have become radioactive by contact with the core. Also, there are materials that are involved in purifying the water used in the reactor, and ensuring that nothing from the core goes out as effluent, etc. These materials are mostly of much lesser radioactive content and toxicity, but their safe handling and disposal does pose problems.*

half-lives and the energy and kind of radiation emitted. The half-life is the interval of time that must elapse during which a half of the nuclei will undergo radioactive decay — the time in which the radioactivity of the material in question decreases to half its original value. Thus in two half-lives, the intensity of the radiation emitted by material will be a quarter of what it was when measurements began; in three half-lives, an eighth as intense, and so on.

The half-lives of the radionuclides in high-level wastes vary from a fraction of a year up to periods of more than a million years (Table 1). Because of the complexity of their chemical behavior and the numerous biological effects that these radionuclides may have, it is difficult to describe their toxicity or effects in terms of simple indices. One such "Hazard Index" gives the amount of water (in cubic meters) required to dilute the material to the "maximum permissible concentration" in public water supplies as allowed by current Federal government guidelines (Figure 4).

The quantity of wastes estimated to be produced in the commercial nuclear fuel cycle in the United States varies, of course, with predictions of how much electrical power will be produced by nuclear reactors. At the moment, there are some 60 commercial reactors licensed to operate in the U.S., with triple that number foreseen by the end of the century. The reactors today provide approximately 9 percent of the nation's electricity. By 1985, the figure is expected to rise to 26 percent. One estimate by ERDA projects that by the end of the year 2000 there will have accumulated at Federal repositories about 2500 cubic meters of solidified waste (a cube 45 feet on a side), containing 10.9 billion curies of radioactivity. At that time, this will be accumulating at a rate of 350 cubic meters and 1.8 billion curies per year.

In large quantities, nuclear fuel waste is extremely dangerous. Even in very small amounts, some of its constituents, including iodine, strontium, cesium, and plutonium, can be carcinogenic or lethal if ingested by human beings, animals, or other living organisms.

Table 1: Half-Lives of Some of the Major Constituents of Radioactive Waste

Radionuclide	Half-Life (Years)
Americium — 241	460
Americium — 242	150
Cesium — 135	2×10^6
Cesium — 137	30
Curium — 242	.45
Curium — 243	32
Curium — 244	18
Iodine — 129	1.6×10^7
Neptunium — 237	2.1×10^6
Plutonium — 239	2.4×10^4
Plutonium — 241	13
Radon — 226	1600
Strontium — 90	28
Technicium — 99	2.0×10^5
Thorium — 230	7.6×10^4
Tritium	13

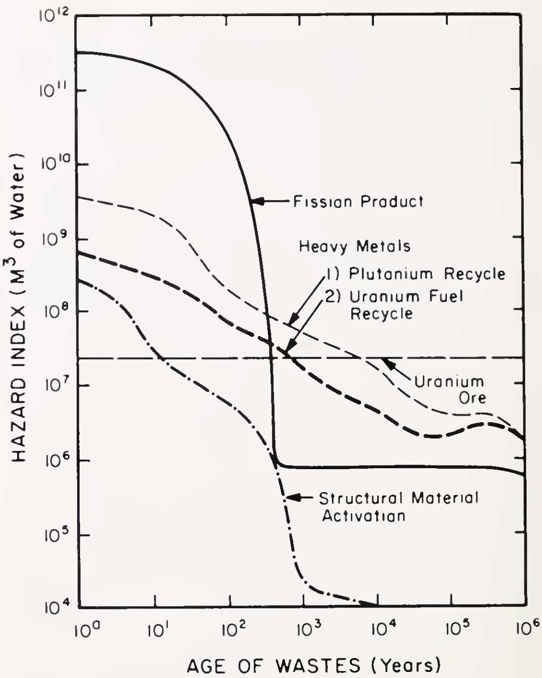


Figure 4. The Hazard Index gives the amount of water (in cubic meters) required to dilute the material to the maximum permissible concentration (MPCw) in public water supplies as allowed by current Federal government guidelines. The MPCw depends in a complicated way on the biological response to the chemistry of the element involved, which organs it may be deposited in, how long the material will remain in the body, the half-life of the radionuclide, the energy emitted at each disintegration, etc. Thus the MPCw varies greatly with the radionuclide. The MPC for air is different from that for water, since the biological response to inhalation is different than that of ingestion. The figure also illustrates the way in which the estimate of Safe Storage Time is a matter of taste. If one chooses safety to be the time when the Hazard Index of the waste equals that of natural uranium ore, then for the plutonium recycle it is about 10,000 years. If the choice for safety is the time when the Hazard Index of the waste equals 1/10 that of natural uranium ore, the time becomes about a million years. If we are satisfied with a Hazard Index for waste ten times higher than for natural uranium ore, the time decreases to a little below 1,000 years. (Courtesy NRC)

There are large variations in the biological effects of radioactive materials. Cesium 137, for example, is extremely dangerous because it is a bone-seeking element that will do severe damage to living tissue. Plutonium, on the other hand, is relatively unlikely to cause damage from mere contact, or even ingestion, since it will be eliminated by the digestive tract. However, it is highly toxic and carcinogenic if inhaled because particles can get stuck in the lungs, or if it gets into the bloodstream, since it is then deposited in the bones.

How Do We Dispose of It?

How shall we finally dispose of the high-level radioactive wastes we have created over the last 30 years and will produce more of in the future? There are three principal alternatives, each of which has numerous sub-alternatives. We can disperse the material, we can store it and guard it, or we can put it somewhere with very difficult access so that we can leave it there safely without continuous concern. A combination of these alternatives is also possible.

The number of sub-alternatives is complicated by the possibility of partitioning: separation of the waste into fractions with different properties, using different management programs for each. As noted earlier, military waste practice already separates 80 to 90 percent of the strontium 90 and cesium 137, the highest heat-producing elements. These elements have half-lives of 28 and 30 years, respectively, and even when separated still must be disposed of.

The question of the composition of the waste is further complicated by the possibility that some portions of the waste might be separated out and put back into a reactor core to be reburned. This idea seems most likely to be useful for some, but not all, of the transuranium elements. The plutonium, of course, can be reburned. Reburning changes the nature of the waste material (the kinds of emitted radiations are changed and the half-lives shortened), but the end products are still radioactive. The neutron fluxes and times required for burning of some of the elements are quite large and transmutation of the fission products does not appear practical with current reactor neutron fluxes.

The transuranics, which must be stored for thousands of years, might also be separated from the fission products, which must be stored for only a few hundred years. Then, the transuranics and the fission products could be stored at separate sites in containers of different integrity.

Dispersion

We all live in a continuous natural background of radioactive material and cosmic radiation. This natural background of exposure to radiation is greater at higher altitudes than lower, and greater in regions of granite rock than limestone rock. If we could take the nuclear waste material and dilute it so that it was distributed in miniscule quantities around the earth, then the increase to the natural background might be so small as to be unmeasurable. This presumably would result in no danger to human or other life, and thus would be safe.

(Certain radioactive gases, such as krypton 85 that is produced by reactors, have been routinely released to the atmosphere in the past. However, this practice is currently being re-examined.)

There are several difficulties with the dispersion concept. One is the basic problem of diluting the material sufficiently and insuring its further dispersion by natural processes. This problem is complicated by the fact that some sediments and soils act as ion exchange filters for some radioactive elements (plutonium, for example), tending to trap and accumulate these materials. Later geological changes, such as erosion, might lead to sudden release of the concentrated materials into the atmosphere or water systems. This filtering property of sediments and soils is regarded as a useful barrier in the geological disposal alternative, provided there is little likelihood for the sudden release of the waste materials.

Furthermore, some biological food chains, particularly aquatic, tend to selectively concentrate materials, such as heavy metal compounds, that are not metabolized or easily eliminated by the organisms. For example, in moving from microscopic organisms up through the food chain to the large carnivorous fishes, concentrations of such materials can be several factors of ten, and as high as 10,000 or more. This occurs because organisms on each food level eat a large quantity of the organisms in the next lower level. For example, carnivorous fish eat many smaller filter-feeding fish, and each filter-feeding fish eats large quantities of smaller animals that in turn eat large amounts of algae. If the materials in question are not eliminated at each level, there is continued accumulation up the chain.

The danger in the dispersion concept lies in the potential for concentration mechanisms, since the whole idea of dispersion would be to dilute the radioactive waste material fairly uniformly.

Storage

The second alternative, to package the material and place it where it can be stored and watched, has been studied in some detail. Engineering plans have been drawn up for packaging and storing it in either surface or near sub-surface vaults. Air or water cooling would be employed to disperse the heat due to its intense radioactivity. Because of the danger to life that would result from accidental or purposeful dispersion of this material, there would be a necessity for very long-term care and guarding. The objection to this form of simple storage is our inability to foresee the nature of human institutions far enough into the future. As noted earlier, the waste materials can remain dangerous for anywhere from hundreds of years to more than a million.

Disposal

The remaining and most attractive alternative is to package the material and put it in a place where it can be left indefinitely without human attention — somewhere with no likelihood that it will be dispersed or taken away, either by natural phenomena or catastrophes, or by human intervention.

The most satisfactory place to put this material would be in the sun, where it would be burned in the extreme temperatures of that great fusion reactor (Figure 5). The cost of such disposal into deep space would be very high; the amounts of material to be disposed of being large in terms of the weights usually launched into outer space. Furthermore, the danger of an accident at launch or before reaching orbit would pose great risks of uncontrolled dispersion of large quantities of highly radioactive material.

Some thought has been given to placing high-level waste canisters in Antarctic ice, thereby allowing the canisters to melt to the bottom of an ice cap with the water refreezing over the container (Figure 6). This possibility does not appear too attractive at present because the velocity and predictability of ice movements over periods of thousands of years are not clearly understood.

The disposal concept that is most favored at the present time involves geological disposal, utilizing a multiple barrier system. The basic idea

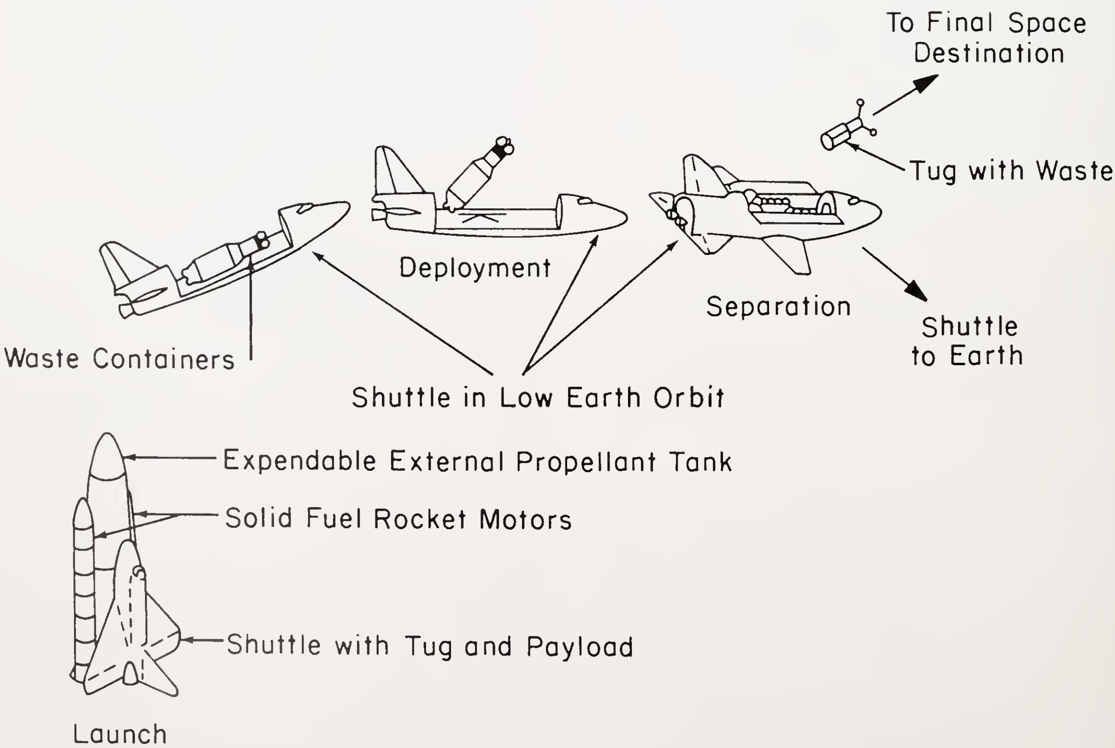


Figure 5. This is a possible space disposal concept. The adoption of this method to manage high-level wastes would be very costly and carry with it the attendant risks of accidents at launch or before entering orbit that could disperse radioactivity into the atmosphere. (Courtesy ERDA)

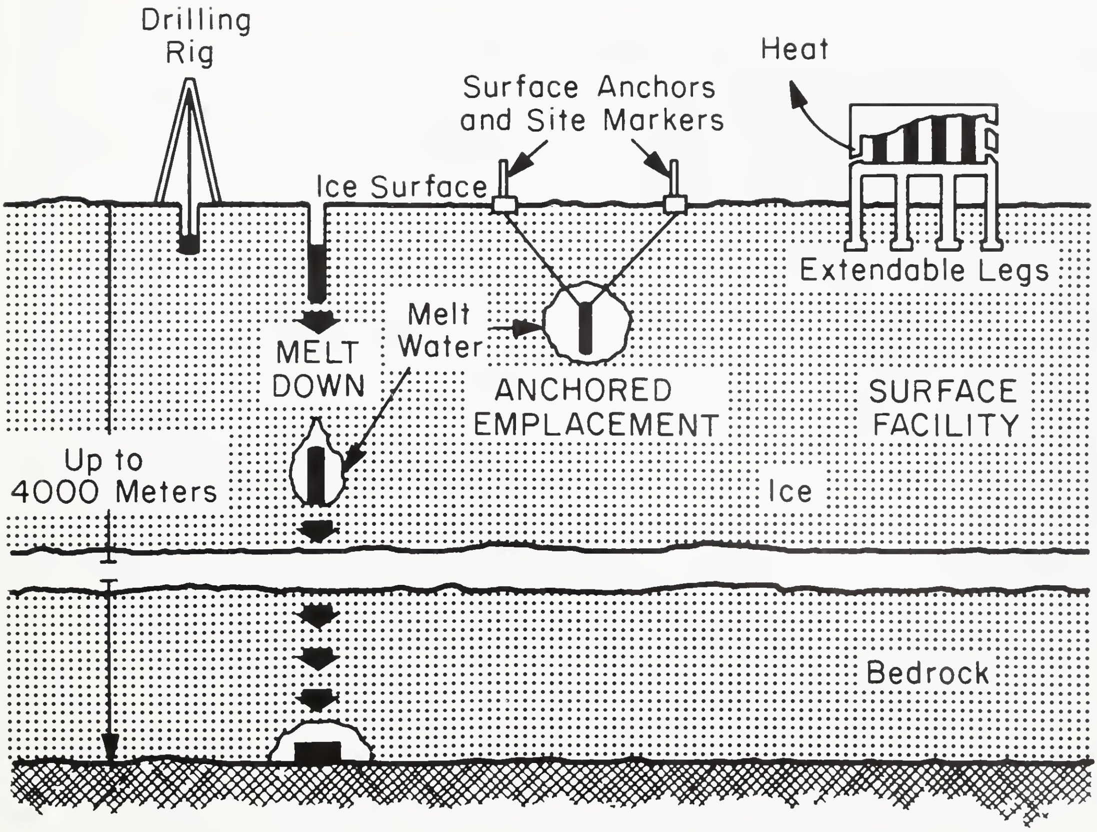


Figure 6. Ice disposal concepts. At left, the melt-down or free-flow concept. Basically, it consists of preparing a shallow hole in the ice and then lowering the canister into the hole, where it would be released and allowed to melt down to the bottom of the ice sheet. Assuming an ice thickness of 3000 meters, the time for melt-down to bedrock would be about 5 to 10 years. In an anchored emplacement method, a hole would be drilled in the ice sheet to a depth of 50 to 100 meters. A waste canister with attached cables 200 to 500 meters long would be lowered into the hole. Melt-down would begin and the descent would be stopped at a depth of 200 to 500 meters by anchor plates on or near the surface. The time for a canister to reach an anchored position, based on thermal probe rates, has been estimated to be 6 to 18 months. The waste canisters could be potentially retrievable for 200 to 400 years. It has been estimated that about 30,000 years would be required for the system to reach bedrock at a typical site. At right, the surface storage concept. In this method, a surface facility would be built supported by pilings. Waste canisters would be placed in cubicles inside the facility, with air cooling provided by natural draft. Eventually, the entire facility would act as a heat source and begin to melt down through the ice. It has been estimated that the facility could be maintained above the ice for a maximum of 400 years before melting down into the ice. (Courtesy ERDA)

behind geological disposal is to find a place in the earth where the high-level radioactive material may be placed, and where the geological evidence indicates there has been and will continue to be great stability for a long period of time. The location should be such that it is highly unlikely to be disturbed by earthquakes, or volcanoes. Ideally, the wastes should remain dry to prevent dissolution of the radioactive material into water that might reach living organisms or man. If water is present, either the surrounding material should trap any escaping waste, or the water should not reach the biosphere until after the radioactivity dissipates. (There are some deep subterranean water bodies that appear to have remained out of contact with the biosphere for hundreds of thousands of years.)

Geological formations that have been suggested in connection with the disposal concept include salt (both massive domed and bedded), granite, shale rock, and sediments (both on continents and under the ocean).

Massive salt by its existence indicates a long-term stability and absence of large amounts of water in the interior of the deposit. Granite may exist in thick, massive formations that, even though somewhat jointed (cracked), do not allow much

water permeability. The geological formation may be protected from water by its surroundings and thus may be a reasonable repository. Some sediments, although permeable to water, are so situated that they are isolated from surface water bodies. These sediments have been isolated for long periods of geological time and are either dry or subject to extremely slow internal water movement. In addition, some sediments have the ability to chemically bind the various materials in the radioactive waste so that even if water did circulate, the materials would be bound in the vicinity of their original point of deposition. This appears to have happened in the case of the "Oklo Phenomenon," an apparently natural fossil reactor in the African country of Gabon where the wastes have remained in position for millions of years.

In addition to placing the waste in a stable geological position, the radioactive material would be transformed into a suitable matrix (glass, ceramic, or composite) and then put into a canister intended to isolate it from its surroundings.

While massive metal canisters may be convenient for shipping, there is little guarantee that they would remain uncorroded in the presence of water for very long periods of time. A hundred to several hundred years would be the most that could be hoped for.

Glasses, ceramics, and some composites have the property of lasting for very long periods of time, remaining stable even when wet, and allowing extremely slow solution (leaching) of the radioactive materials. Thus, mixing the radioactive material with other materials from which could be formed a glass, ceramic, or composite material would in itself form a barrier to dispersion or dissolution.

Even if immersed in natural water, glass or ceramic might leach at so slow a rate that periods between hundreds and thousands of years would be required before they could be completely dissolved. Even longer leach times may be found possible in the future.

Thus, the most elaborate version of such a multiple barrier containment system might include transformation of the high-level waste into a glass or ceramic or other solid material that would dissolve and leach at extremely slow rates. Then, this material would be put into a glass, ceramic, or metal canister that would be a second barrier. Finally, the canister would be inserted into a geological milieu that would be expected to be undisturbed for times up to and beyond a million years. In addition, the geological milieu might be expected to have the property of trapping by ion exchange any of the materials that might leach out should circulating water penetrate the canister.

This multiple barrier system might be shown to be more elaborate than necessary. One possible alternative would be to simply drill a deep hole into a geological formation, either on land or under the ocean, and then insert the waste material in solid or liquid form into the hole, letting the heat generated from the radioactivity melt the surrounding rock into a glassy self-containing material.

Given the design and configuration characteristics of the multiple barrier system, there are still a number of problems that arise in considering how to get to the final situation. These include questions on the nature and dangers of the material to be transported (this affects the form of the material), the engineering problems of constructing a geological repository, the placing of material in it, and the sealing of it.

The question of retrievability also must be considered: should the material be emplaced so that it is impossible or extremely difficult to remove, or should the repository be designed so that it can be retrieved? The answer seems to depend on several factors — the level of confidence that the sealed material will remain in place for the times predicted; the degree of concern that if retrieved it may be used for illicit weapons production*; and the extent to which future generations might develop better means for disposal, or wish to retrieve the wastes for some other purpose.

The integrity of the disposal is probably the key criterion: retrievability would have to be achieved without increasing the probability of accidental dispersion, and would have to be difficult enough so that conversion to illicit purposes would be unlikely. If the wastes are well sealed, it is not probable that future technology would make it desirable to do something "better" with them. Since we do not know the possible future uses of waste material, it is hard to weigh the value of retrievability for these uses against any risks that retrievability designs might pose.

**Whether waste is useful for weapons production depends on whether the plutonium has been separated from it or remains in the waste.*

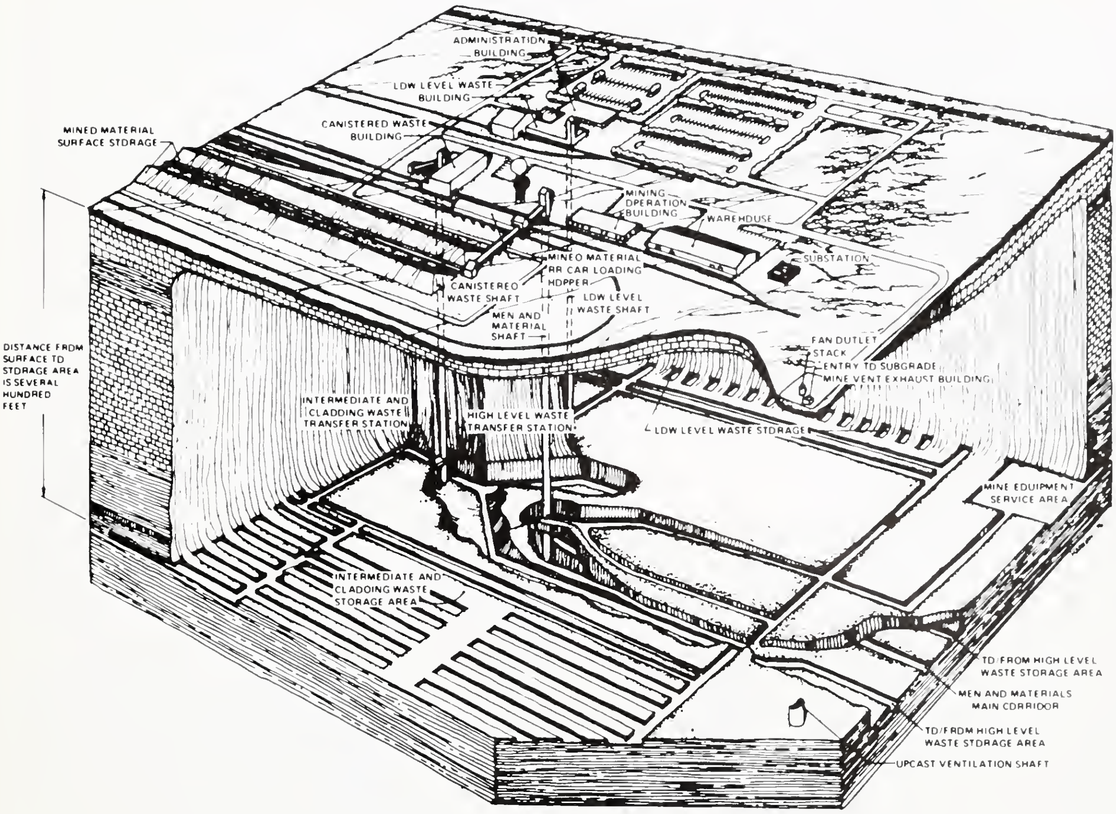


Figure 7. Rendering of a geological repository for low-level, medium-level, and high-level radioactive wastes. At the present time, the government is examining a number of sites throughout the United States for such a facility. (Courtesy ERDA — Office of Waste Isolation, Oak Ridge, Tenn.)

Geological Repositories

The United States is actively examining a number of potential land sites for geological repositories (Figure 7). These are favored as the prime waste disposal option and include both domed and bedded salt areas and sites with shale and granite (Figure 8).

Given the variety of such sites inside the United States, why consider the sub-seabed for a repository? There are both political and scientific reasons. It is possible, even with reasonable technical assurances that repositories in the United States would be safe, that the public will prefer that the wastes be kept outside the country. This feeling may well be exaggerated by the "don't put it in *my* backyard" kind of politics that we are already familiar with from garbage and sewage disposal problems.

Further, some countries, such as Britain, the Netherlands, Belgium, and Japan have essentially no land options for high-level wastes and must either get another country to accept their wastes or place them in some internationally agreed upon repository, such as a sub-seabed site in a remote, deep area of the ocean. In addition, the international desire to avoid proliferation of nuclear weapons and to pool resources for reprocessing and waste disposal might lead to support for the sub-seabed as a useful repository, if technically and biologically sensible.

From the technical point of view, parts of the ocean floor display long, stable geological histories and may have suitable properties for isolation. In some ways, these areas may be superior to land sites. These points are discussed in subsequent articles.

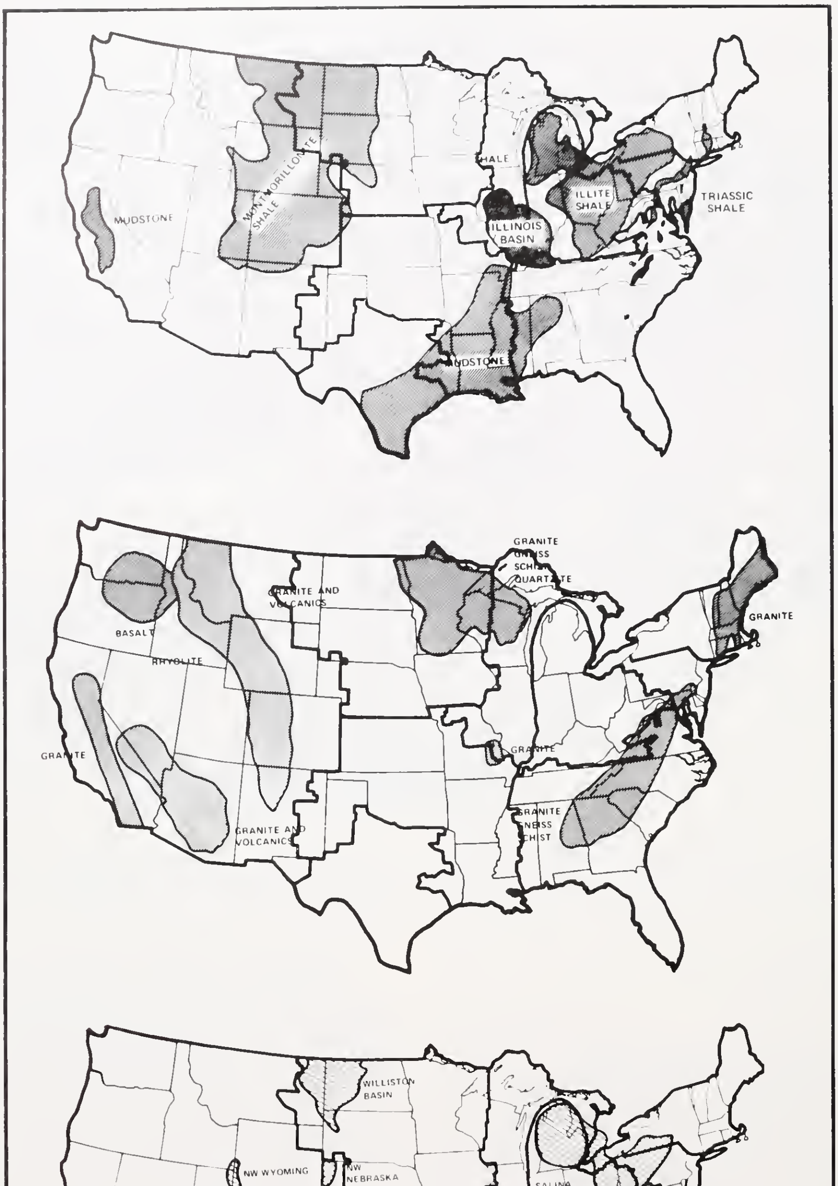


Figure 8. The top map shows the distribution of argillaceous formations in the United States; the middle, various crystalline formations; and the bottom, salt rock deposits. (Courtesy ERDA)

At the present time, no nuclear fuel is being reprocessed in the United States; the previously reprocessed waste (mostly military and some commercial) is in storage. Spent fuel assemblies that have been removed from reactors are stored in water pools at the reactor sites. Such storage is satisfactory for decades from a technical point of view (eventually, corrosion of the rods and solution of the waste in the pool water would become a problem), but increasing quantities so stored would clearly give rise to justified public apprehension. The "Vermont Yankee" court decision and other public situations mentioned at the beginning of this article make it clear that public views are unlikely to permit large expansions of nuclear energy unless a sensible, long-term management program for the wastes is developed and acted upon. It seems likely that a decision to solidify the wastes and put them into geological repositories will be made very soon; it will then take five to ten years to find and develop suitable sites.

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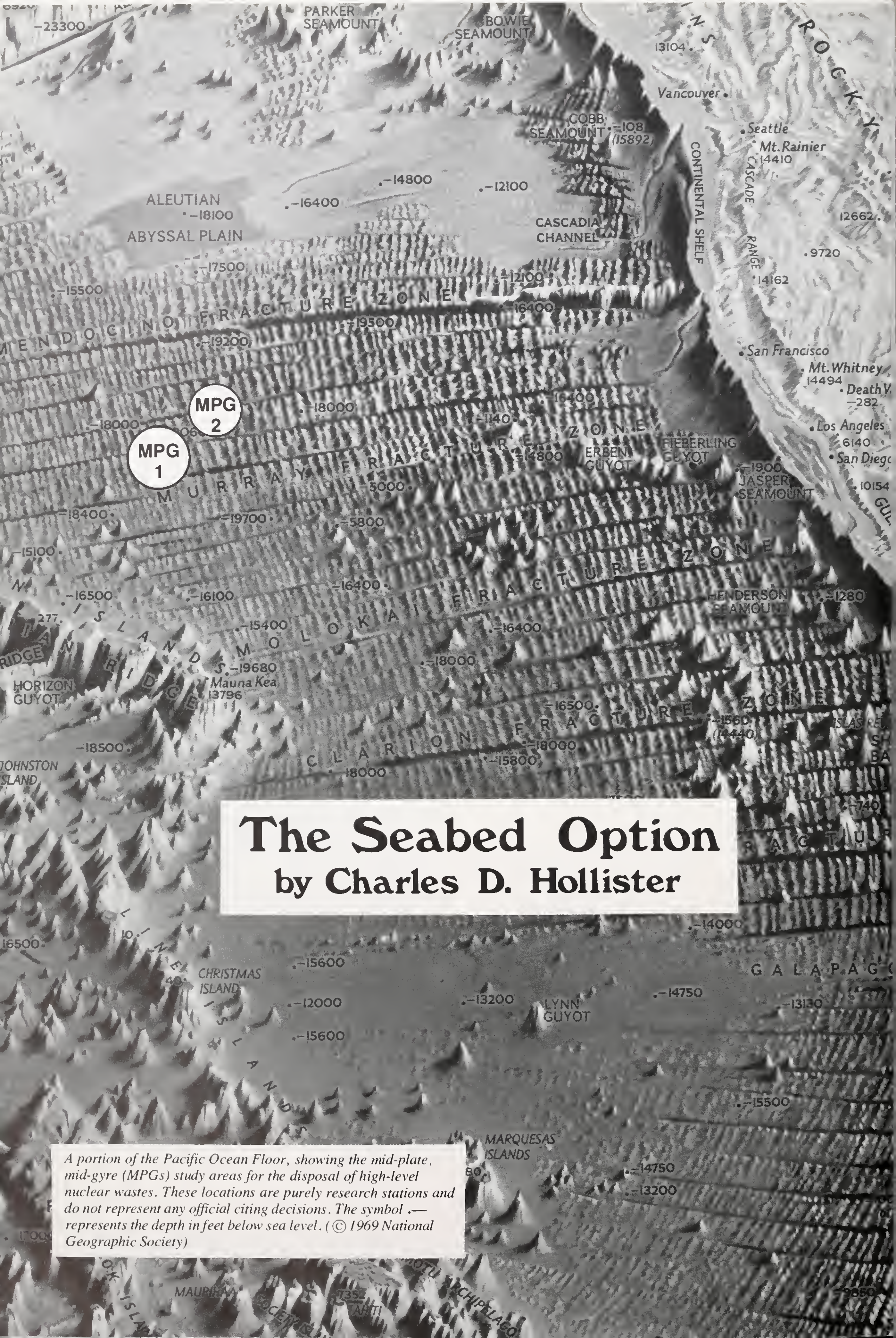


The Seabed Option

by Charles D. Hollister

A portion of the Pacific Ocean Floor, showing the mid-plate, mid-gyre (MPGs) study areas for the disposal of high-level nuclear wastes. These locations are purely research stations and do not represent any official citing decisions. The symbol .— represents the depth in feet below sea level. (© 1969 National Geographic Society)

"Where on earth can we permanently isolate toxic radioactive waste that is dangerous to man and his food chain for periods of a million years or more?" This question was first posed to me in 1973 by Dr. William P. Bishop, who was then with Sandia Laboratories, a government research facility at Albuquerque, New Mexico. My initial reaction was a flat "not in our ocean; not in my own backyard." The prospect of a contaminated ocean that might hurt my children or any other human beings turned me against the idea almost completely. But a number of tantalizing questions persisted. What exactly would be entailed in the disposal of high-level radioactive waste in the ocean? Could the waste material just be dumped into the water? Could it be pushed off the fantail in a canister and allowed to fall to the bottom? Not likely. Probably, it should be buried within the geological formations beneath the sea floor — in some stable, useless, environmentally predictable region, an area that would remain unchanged for the next several million years.

There were other questions to wrestle with, too: should we perhaps just terminate this country's headlong rush into the development of nuclear power, with its attendant waste management problem? We might, but even if we did, the problem of what to do with existing wastes would still be with us. As mentioned in the lead article, we already have many tens of millions of gallons of wastes from our weapons industry stored in tanks in the ground, some of which have leaked badly. These wastes must be disposed of permanently, and in the not too distant future.

And so, as I became more deeply involved in this problem, it seemed sensible to search for the least valuable piece of real estate on the planet, hopefully a region where tranquility and stability are maximized, where no earthquakes, volcanoes, erosive currents, glaciers, or man would likely disturb the repository during the time needed for the toxic material to decay to approximately 10 half-lives. It also seemed sensible to put the waste in areas where biological productivity would be low.

One came back to the possibility of the deep seabed — the centers of oceanic gyres (great circular currents) and of lithospheric plates, the so-called MPGs (mid-plate, mid-gyre areas).

Oceanographic data acquired since the late 1960s suggest that the ocean floor is continually built and destroyed by dynamic processes of crustal movement. This process, once called continental drift, has come to be known as plate tectonics or sea-floor spreading. The globe is made up of a number of solid-rock or lithospheric plates composed of oceanic and continental crusts. These plates move in predictable directions at predictable speeds. They collide in regions of seismically active deep-sea trenches or of mountain building. Plate boundaries thus can be areas of *crustal destruction*, where the edges of plates are thrust under or over other plates. They also can be areas of *crustal construction*, where new crust, if the earth's diameter is to remain constant, is made at a rate equal to the destruction rate. Such growth takes place at the center of the Mid-Oceanic Ridge, a globe-circling and spreading welt of about 40,000 kilometers in length. Along this active volcanic line, new molten basalt is constantly being injected into the ridge, which widens at a rate of 2 to 20 centimeters a year.

Rejected Options

Why not put the high-level waste into the deep-sea trenches instead of the mid-plate, mid-gyre region? Because the deep-sea trenches, popular press accounts to the contrary, are unpredictable (material from their bottoms has been thrust up onto the continent in the past) and unstable. In addition, they are usually near continents — and, therefore, man — and often lie beneath biologically productive ocean waters. Another, perhaps minor, consideration is that at present we do not have the technology for penetrating crustal rock at trench depths.

The only direct data we have about the structure and composition of crustal rock have come from a few holes drilled with great difficulty through approximately a half-kilometer of basalt in shallow Mid-Oceanic Ridge crest areas. Core samples taken on the Mid-Oceanic Ridge suggest that this rock is broken up and badly fractured, with perhaps very high bulk permeability. None of the data so far suggest that shallow ocean crustal rock is monolithic. These considerations lead us, at least for the present, to the thought that emplacement of wastes in the crustal rock, at least at shallow depths, would not be prudent. An abyssal midplate region should be drilled, however, before we finally abandon this disposal option, as it is conceivable that crustal rock is effectively healed and sealed — leading to a very low permeability — by the time it reaches midplate depths of 5 kilometers (a journey requiring at least 50 million years of sea-floor spreading).

Placing the high-level waste on top of the sea floor simply by kicking a canister off the fantail effectively puts the waste directly into the biosphere, as it is difficult to conceive of making a canister that would survive without leaking for hundreds of thousands of years in the corrosive marine

environment. Any leak, either during the disposal operation or after, would inject radioactive material into the marine ecosystem. From samples, photographs, and current meter data, we know that the energetics of the biological and physical processes of the sediment/water interface (benthic boundary layer) can be very high and very unpredictable (see page 41).

Another suggested disposal option is to dilute the high-level waste by dispersing it into the ocean waters. This method, favored by some western European countries, has been and is being used to dispose of low-level wastes.

Calculations show that the waters of the ocean are not vast enough to take all of the waste from all of the military and industrial sources without being contaminated beyond safe limits within the next few decades. Dispersion and concentration mechanisms — biological, physical, and chemical — are so poorly known that researchers are not yet ready to predict possible pathways and rates of transfer from ocean bottom to man's food chain.

The MPG Seabed

Given the serious defects in most ocean disposal options, I felt that the geologic formations beneath the sea floor should be assessed with a view toward establishing some site selection criteria. Initially, it seemed prudent to avoid areas where earthquakes had been recorded. This left the central portions of large plates, some of which are thousands of miles from areas of crustal destruction. Here the sea floor is apt to be covered with a blanket of soft, sticky, chocolate-colored oxidized clays. These clays have certain chemical and physical properties that, if taken together, might conceivably provide a suitable waste isolation medium, even assuming total failure of the canister after emplacement — obviously the worst possible case. The ion-retention and permeability characteristics of these clays might be adequate to chemically and physically contain the waste for the periods needed (see pages 26 and 31).

This was the concept I discussed in the spring of 1973 with Dr. Bishop, who is now with the Nuclear Regulatory Commission (NRC). He then invited me to speak at Sandia Laboratories. The resulting two-hour seminar a few months later was devoted to global concepts of oceanographic processes and words about predictive geology and plate tectonics. I further developed the concept of a potential mid-plate, mid-gyre repository in lay terms and talked about the possibility of matching rates of radioactive decay to rates of release. My concluding remarks focused on the repository potential of unconsolidated clay sediments in those ocean basins where, from core sample data, we had a continuous record of millions of years of tranquility and geological stability.

The first task after the seminar was obvious: assemble a group of competent scientists, representing all the necessary oceanographic disciplines, and bring them to a multidisciplinary informal workshop to further evaluate the idea of seabed disposal. The scientists would play the role of devil's advocates and then, if the concept was still viable, identify the research tasks that would be necessary to adequately test the hypothesis. My first contact was with Dr. Vaughan T. Bowen, Senior Scientist at the Woods Hole Oceanographic Institution, Department of Chemistry. He has a long-standing research program with the Atomic Energy Commission (now ERDA and NRC) that deals with the problems of radionuclides in the environment. I knew he could give good advice on the validity of the concept and the merits of a process-oriented oceanographic research program. Dr. Bowen's immediate reaction was, "I'd be glad to help. Assemble the team. Take care." That was in the spring of 1973, and now, in the winter of 1977, we ask: Where are we? Where are we going?

The initial team consisted of Bowen; Robert Hessler, deep-water benthic biologist from Scripps Institution of Oceanography; Ross Heath, sedimentologist-geochemist, then of Oregon State University, now of the University of Rhode Island; Dennis Hayes, a geophysicist from Lamont-Doherty Geological Observatory, New York; Bruce Taft, physical oceanographer, then at Scripps, now at the University of Washington; and Armand Silva, civil

engineer studying properties of deep-sea sediments, then head of the Department of Civil Engineering at Worcester Polytechnic Institute, now at the University of Rhode Island.

After assembling this team, other needs for expertise came to light. We called on John McGowan of Scripps, a specialist in biological processes of the upper water masses; Terry Ewart, a seagoing physicist at the Applied Physics Laboratory of the University of Washington, an expert in open-ocean diffusion experiments. Meanwhile, Peter Rhines of Woods Hole and John Swallow of the Institute of Ocean Sciences in Britain provided advice in theoretical and physical oceanography. John Ewing, chairman of the Department of Geology and Geophysics at Woods Hole, also provided advice and guidance on acoustical/geophysical problems and on global patterns of sediment accumulation. During succeeding years, we have sought and will continue to seek more advice from many other experts.

Before seabed disposal of radioactive wastes can be considered acceptable, we must establish to the satisfaction of both scientists and the public at large that:

1. The sediments have large enough sorption coefficients to prevent each radionuclide from escaping to the ocean.
2. The permeability of the sediments is so low as to minimize migration of the waste products when they are leached eventually into the pore water.
3. The first two factors, when taken together, will effectively isolate the waste within the geological medium for a period of at least several million years.
4. Geologic processes over the disposal area have been uniform and further that the site has suffered little or no environmental disturbances over the last ten million years.
5. The emplacement technique itself or the heat generated by the waste will not seriously affect the necessary containment.

The task of the Seabed Emplacement Program, which is supported by the Energy Research and Development Administration, is to determine if *any* sub-marine geologic formation can contain radioactive waste long enough for it to decay to harmless (background) levels (Figure 1).

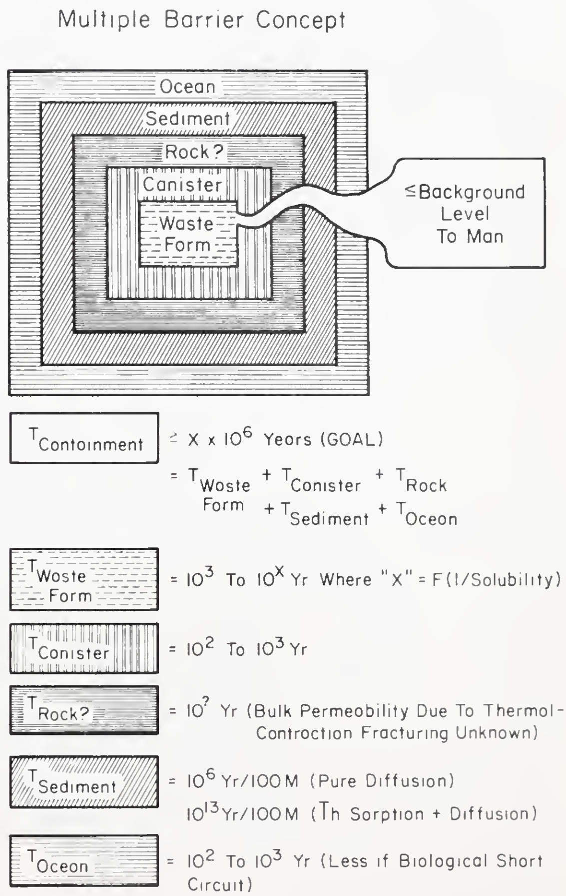


Figure 1. Diagram of the seabed containment model that forms the basis for the studies described in this article. Note that the sediment barrier appears to be the most promising with respect to breakthrough time.

Site Selection and Results

During the first workshop, we chose a study area (MPG-1) in the middle of the central North Pacific about 600 miles north of Hawaii. The area between the Murray and Mendocino Fracture Zone had previously been surveyed bathymetrically by the National Oceanic and Atmospheric Administration (NOAA). This meant we could get on with acquiring other more specific geological, geophysical, and oceanographic data without first having to map the bathymetry.

We immediately deployed current meters so that we could begin to measure near-bottom circulation patterns. In the North Pacific, current measurements over long time periods were not available. Therefore, in 1974, a current measurement program, headed by Bruce Taft, was initiated to obtain records spanning a year and a half. The current speeds that we measured in the area were low; in fact, a significant number of zero speeds were recorded at each meter. The records were dominated by tidal currents, which is typical of most deep current records where the energy of the fluctuations exceeds the mean energy of the flow. The magnitude of the fluctuations was approximately 2 to 4 centimeters per second. These were comparable to the near-bottom measurements of 5300 meters in the western North Atlantic.

Since the distance of the meters above the bottom was similar to the height of the abyssal hills (roughly a hundred meters), it is possible that the local topography influenced the direction of the mean flow. Visually, the data suggested that the bottom currents have major oscillations in direction for a period of about 150 days. The most energetic Pacific fluctuations appear to have a longer time span than those in the North Atlantic. However, even taking into consideration the low velocities measured, it appears that the bottom water could flow across the entire Pacific Ocean in 100 to 1,000 years. Clearly, the near-bottom circulation at MPG-1 is far from stagnant. Thus, any material released into the water will be advected away at a rate much greater than the decay rates of the longer lived radionuclides.

The new data and geological samples — collected by research vessels from Columbia University, the University of Washington, and the University of Hawaii — allowed us to construct sediment thickness maps to help us determine if the sediment layers evenly blanketed the region. We concluded that our first mid-plate, mid-gyre study region, covering about 40,000 square kilometers centered at 31° 30′N and 158°W, is more or less evenly covered with about 20 to 40 meters of unconsolidated sediment. This layer generally thickens toward the Murray Fracture Zone along the southern border of the area. The low, rolling basement topography consists of north-south ridges that are obvious in our sediment thickness maps (Figure 2).

The abyssal hills in this region have about three-quarters as much sediment cover as the valleys, suggesting at least some downslope concentration of sediment, perhaps due to sediment resuspension by bottom organisms with gentle winnowing by bottom currents.

A sub-bottom acoustic reflector (a geologic boundary that reflects sound waves transmitted from a surface ship) occurs about 10 to 15 meters below the bottom. A standard one-ton oceanographic piston corer on the research vessel *Vema* did not penetrate this layer despite repeated attempts. However, in October of 1976, we obtained a 24.4 meter (80 foot) core with the Woods Hole Giant Piston Corer aboard the *C/S Long Lines*, a cable-laying ship. This core contained altered ash layers, including one with a hard manganese coating, at about 10 meters below the bottom that appears to correlate with the sub-bottom acoustic reflector. The sediments at the bottom of the core were laid down more than 65 million years ago (as dated from their contained fish-teeth and scales by William Riedel and Pat Doyle of Scripps).

The core consists of what appears to be a continuous sequence of mostly brown oxidized clays (mean grain size 2 micrometers) interspersed with a few altered ash layers. Such layers of altered ash are often found in deep-sea clays; they record volcanic eruptions from islands or seamounts upwind and

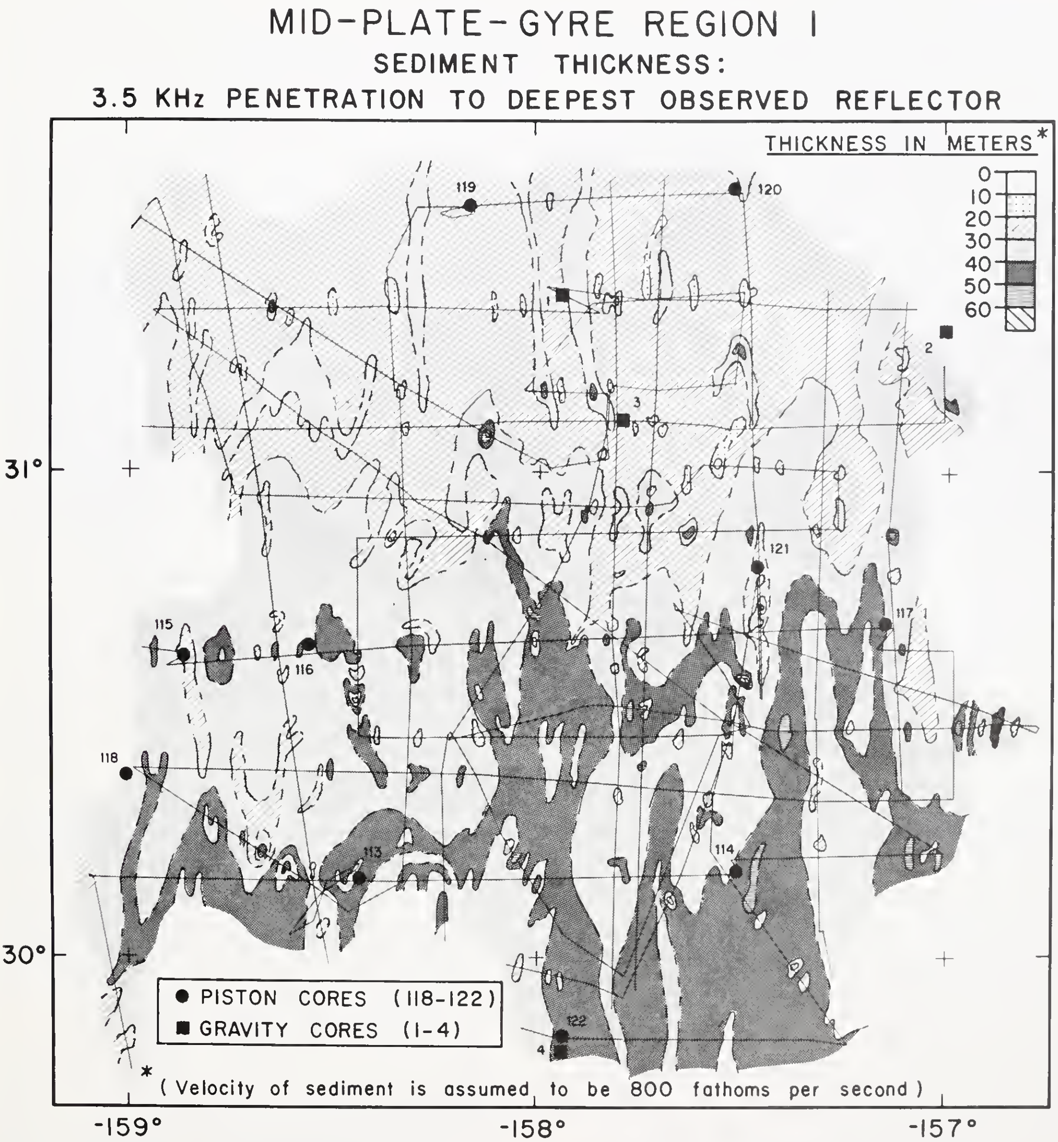
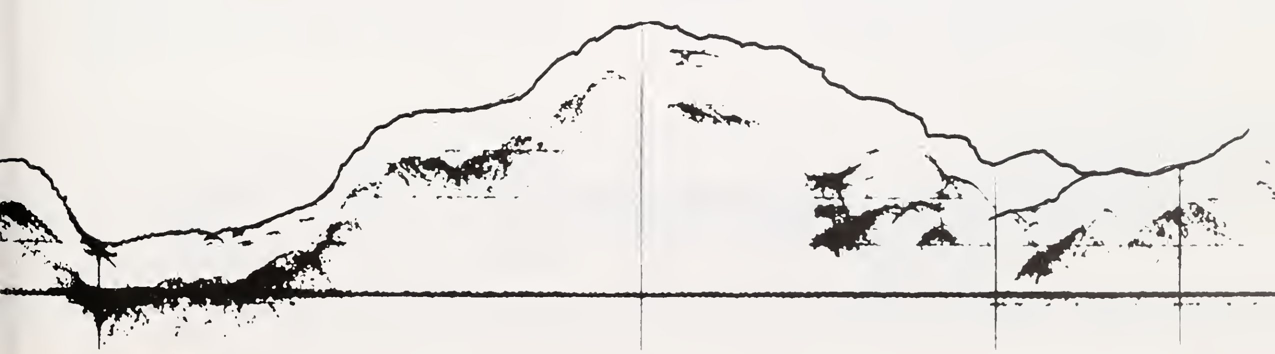


Figure 2. Distribution of sediment thickness in the Mid-Plate, Mid-Gyre Region 1, approximately 600 miles north of Hawaii. The sediment pretty much blankets the basement topography, which has a north-south lineation.



upcurrent of the region. Future deposition of such ash would not be harmful from a disposal point of view, as the fine volcanic material would settle slowly from the sea surface like gentle rain. Thus, preliminary analysis of the long core supports our initial prediction that the sediments in the mid-plate region would not vary much with depth, indicating that depositional conditions have been uniform for tens of millions of years.

In order to extend our data base and further assess the mid-plate, mid-gyre environment (and perhaps find thicker sediments on an even flatter bottom), we made a geologic cruise on the Oregon State University vessel *Yaquina*, with Ross Heath as chief scientist, to a second area (MPG-2) approximately 700 miles to the northeast of MPG-1. Unfortunately, at this location, we found that the sediment cover was even thinner (about 20 to 30 meters). Again, though, we detected a sub-bottom reflector that could be correlated with a series of altered volcanic ashes that were sampled by 10 to 12 meter piston cores. Due to the thinner sediment cover, the MPG-2 area does not appear to be as useful a study region as MPG-1. However, studies of the MPG-2 cores by Heath have shown that sediment processes have been depositional and uniform over a fairly large area for at least the last 20 to 30 million years (see page 26).

These studies, which included paleomagnetic measurements of core samples, also showed that the sediment blanket, although variable in thickness, represents a continuous record of deposition. However, because the clays contain few fossils, we can make only crude estimates of the rates at which the deposits have accumulated. A careful analysis of fish-teeth debris and other components will have to be undertaken to confirm the paleomagnetic results. It is particularly important that we determine whether any of the sediment section is missing, as this bears on our ability to predict future erosional events that might uncover a repository.

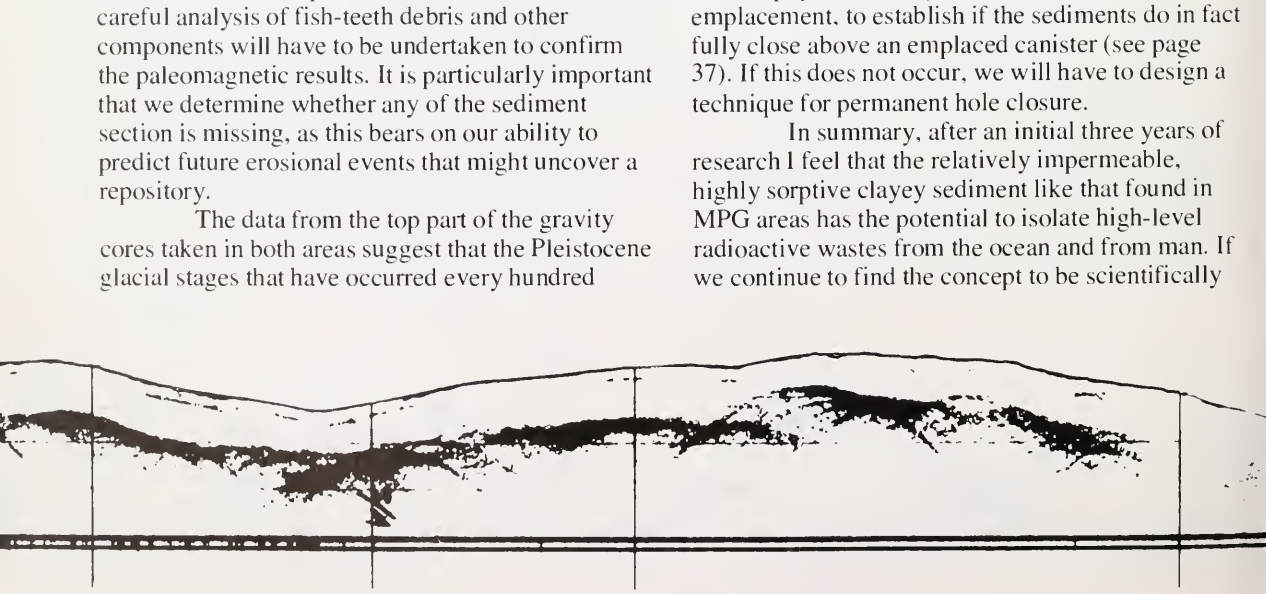
The data from the top part of the gravity cores taken in both areas suggest that the Pleistocene glacial stages that have occurred every hundred thousand years in the recent geologic past increased the rate of sediment supply but did not otherwise affect the abyssal environment in these regions. Thus, it is reasonable to conclude that the next major glaciation, which likely will begin in the next 1,000 to 10,000 years, will not disturb the MPG environment in a harmful way from a disposal point of view.

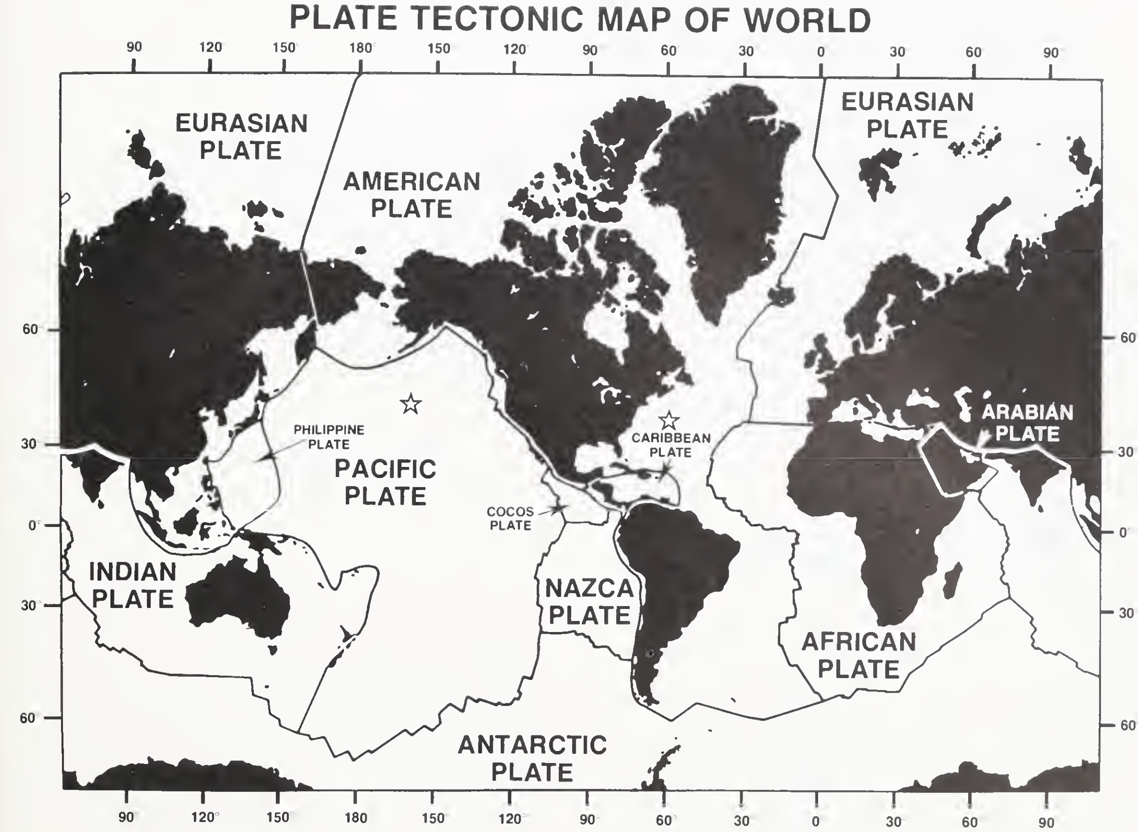
Records gathered during the Giant Piston Core cruise indicate that some of the sub-bottom reflecting horizons over distances of tens of kilometers are discontinuous. They range from a few kilometers in lateral extent to less than a kilometer. This probably reflects variable alteration (including cementation by hydrated ferromanganese oxides) of ash layers. Nonetheless, because such data may indicate some lateral variability, it will be necessary to take a series of long cores covering the full range of acoustic conditions in any MPG area proposed for even a pilot study testing of seabed disposal.

Future Plans

We are still trying to prove the adequacy of the sediment barrier to waste migration. Our next step is to identify the best possible sediment with respect to the retention of radionuclides, whether it be oxidized red clay, reduced hemipelagic clay, or biogenic ooze. Sediments that have adequate containment properties will have to be studied at sea to determine whether they can be found in sufficient thickness in MPG-type settings. If so, we will determine whether the sediment is uniform over large areas. Finally, once a barrier is proven from chemical and permeability measurements, we will determine in situ the physical and dynamic response to emplacement, to establish if the sediments do in fact fully close above an emplaced canister (see page 37). If this does not occur, we will have to design a technique for permanent hole closure.

In summary, after an initial three years of research I feel that the relatively impermeable, highly sorptive clayey sediment like that found in MPG areas has the potential to isolate high-level radioactive wastes from the ocean and from man. If we continue to find the concept to be scientifically





The plates of the world are in motion relative to one another. They are either slowly moving apart, with the creation of new crust, moving together with the destruction of old crust, or moving past one another. The stars indicate areas where initial research has been undertaken on the disposal of high-level radioactive wastes. These locations are only generic study areas of the U.S. Energy Research and Development Administration's Sub-Seabed Program and do not represent specific site decisions.

sound, we must present our data as soon as possible, so that the seabed can be fully examined by disinterested experts, and compared to other disposal alternatives. Certainly, there appears to be no scientific or technical reason to abandon the seabed disposal concept at this time.

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Barriers to Radioactive Waste Migration

by G. Ross Heath

Regardless of the method that is ultimately chosen for the disposal of high-level radioactive waste, the definition of success must be that *there is almost no likelihood of radionuclides reaching man's environment while they are still radioactive*. Since one of the plutonium isotopes in the waste has a half-life (the time required for half the initial amount to decay away) of almost 400,000 years, the waste must be isolated from man for at least a million years. One of the main tasks of the Energy Research and Development Administration's seabed disposal program is to find out the speeds at which waste radionuclides buried in the seabed can move up through the sediment. If these speeds are so slow that all the radioactivity will decay long before any element can reach the sea floor, seabed disposal is environmentally acceptable (regardless of its political, technical, economic, or legal feasibility).

Three barriers lie between wastes buried in the seabed and the ocean. They are: 1) the glassy waste material itself; 2) the canister; and 3) the sediment that surrounds the canister.

An additional barrier might be provided by burial of the wastes in volcanic rock that lies beneath the sediments of the seabed. Recent deep drilling by the *Glomar Challenger*, however, suggests that the first few hundred meters of volcanic rock beneath the sediments is laced with fractures that formed as the rock cooled after eruption. At worst, these cracks could breach the barriers between man and waste mentioned earlier by allowing seawater to circulate freely through the rock. In any case, they prevent us from making reliable estimates of the speed at which various elements migrate through the rock, because neither their size nor spacing are uniform from one drillhole to another.

The Waste Form

The liquid waste produced during the reprocessing of reactor fuel rods is basically a solution of radioactive and nonradioactive elements in nitric acid. This solution is very corrosive, generates large amounts of heat, and is highly radioactive. Present plans call for solidification of the waste by evaporation of the acid followed by fusion of the salts into a glass, probably a borosilicate glass much like that in ordinary bottles (Figure 1). This glass is much easier to handle than liquid waste, and has the additional advantage that it is quite insoluble. Thus, the glass itself forms the first "barrier" in the sense that elements are released to the surrounding environment at least a million times more slowly than they would be from the soluble nitrate salts or from the solution before evaporation.

Figure 1. Silicate glass such as this would form the first "barrier" to the escape of radioactivity from the canister. The high-level wastes would actually be incorporated into the glass in a ratio of about 25 percent waste to 75 percent glass. (Courtesy ERDA)

Several questions about the properties of this waste form are still unanswered. Exact leach rates for most of the radioactive elements are not known because a final decision on the best type of glass has not been made. In addition, few if any leach experiments have been carried out using solutions resembling sediment pore waters, or at temperatures and pressures anticipated in the seabed after emplacement. Another question of concern is the long-term stability of the glass. The heat produced by the radionuclides during decay will ultimately devitrify the glass. This process converts the waste from a uniform, very thick "liquid" (glass) to a mass of tiny crystals. From our experience with natural volcanic glasses in deep-sea sediments, we know that devitrification greatly speeds up the rate at which elements are released from the glass. Thus, the effectiveness of a glassy barrier may be very different if devitrification occurs in a few years rather than a few centuries. At the same time, we know that radiation produced by decay of the waste radionuclides damages the structure of either glass or crystals, making these materials even more vulnerable to solution.

In any case, a glass waste form is unlikely to confine the radioactive elements for more than a thousand years — far less than the several million required. Since most of the heat produced by the waste is given off in the first few hundred years, however, it is important that we determine how effective the "waste form" barrier is.

The Canister

To confine the glassy wastes during processing, storage, and transportation, they will most likely be sealed in metal canisters. Glass or ceramic canisters are possible alternatives for some disposal options, but may be less suitable for seabed disposal because of the strength requirements for handling and shipment. The canister must be able to dissipate the heat from newly packaged waste, as well as be conveniently handled, so present designs center around cylinders about 1 foot in diameter by 10 feet long (Figure 2). When newly filled, such canisters will give off 10 to 30 kilowatts of heat as well as radiation so intense that anyone foolish enough to spend even a second at a distance of 3 feet from the canister would be exposed to as much radiation as the Nuclear Regulatory Commission presently permits people working with radioactive materials to receive during their entire lifetimes.

If seabed disposal ever becomes a reality, the canisters will be made of a metal or alloy that will resist corrosion as long as possible. Unfortunately, seawater (which is much like sediment pore water) is an extremely corrosive natural fluid. The only candidates for canister materials that appear suitable at present are titanium and zirconium alloys. Research to better define the behavior of these materials in pore waters is being carried out by metallurgists at Sandia Laboratories, a government research facility in Albuquerque, New Mexico. Their best estimate at present is that material capable of confining the wastes for a few thousand years can be found if reasonable temperature levels are maintained (not greater than 200 degrees Centigrade). Again, this is far from the minimum of a million years of total containment that is needed. Nevertheless, as is the case for the waste form, this period is long enough to allow the waste to dissipate most of its heat before it begins to interact with the surrounding sediment, thereby enormously reducing the likelihood of rapid upward transport of radionuclides in convection currents that could be produced by the hot waste.

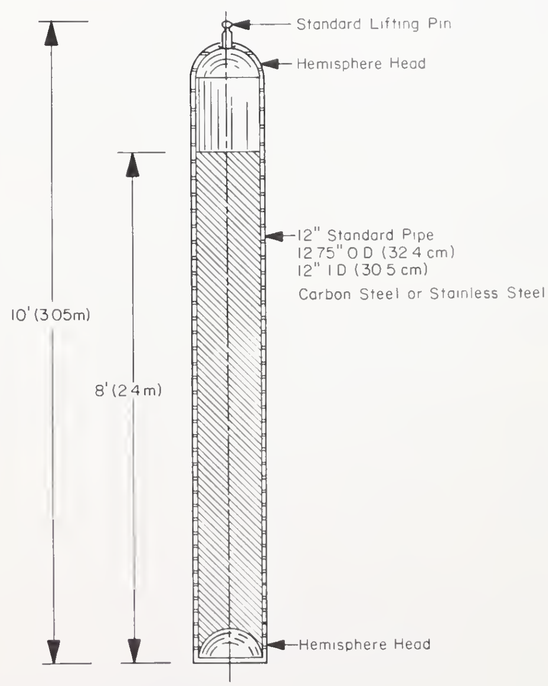

Figure 2. The proposed standard canister for high-level, low-level, and intermediate-level wastes. (Courtesy ERDA — Office of Waste Isolation, Oak Ridge, Tenn.)

Sediments of the Seabed

Deep-sea clays that form a large portion of marine sediments have a number of properties that make them attractive to a geochemist interested in using

them as part of the barrier sequence. They are extremely fine grained (most particles are less than 1 micrometer [1/25,000 of an inch] in diameter). As a result, they have low permeabilities (see page 34). They also have very large surface areas per unit volume of sediment, an important attribute in reactions between dissolved waste elements and clays, in addition to well-known and extensively studied abilities to extract (sorb) metals from solutions.

In examining the barrier properties of deep-sea clays, let us first consider where there is no flow of water through the sediment and where emplacement of the canister has no effect on the seabed. Reactions in this case are much like those in nature, where one type of sediment is buried by another.

For waste elements that react little or not at all with the sediments (for example, chlorine and tritium), the time required for the first molecules to diffuse from the canister to the sea floor is the depth of burial squared, divided by the diffusion coefficient for that element in the particular sediment. Based on a diffusion coefficient of 3×10^{-6} square centimeters per second (an average value for deep-sea sediments), it would take waste chlorine buried 100 meters (328 feet) below the sea floor a million years to appear in the ocean. This time is beginning to approach the isolation time required for high-level waste. It is certainly encouraging enough to lead us to study the migration of elements that *do* react with the sediments. The waste elements with long half-lives, such as plutonium, fall into this latter group (Table 1).

A solution of metal in a clay sediment equilibrates itself so that some of the metal is sorbed to the sediment and some remains dissolved in the pore waters. The ratio between the sorbed and dissolved fractions is called the distribution coefficient. Because only the dissolved fraction diffuses through the sediment, the rate of diffusion of a reactive element is much slower than the rate for the nonreactive elements discussed earlier. In fact, we can get a good idea of the diffusion rate of a reactive element by dividing the nonreactive rate by the distribution coefficient. The nonreactive rate is about a hundred meters per million years. To provide a reasonable safety margin, distribution coefficients for long-lived waste elements should be more than 10, and preferably more than 100.

The measurement of these coefficients is one of the major tasks presently being undertaken by Sandia Laboratories and by our laboratory at the University of Rhode Island. This is a long-term project, because the coefficients must be determined for the important radionuclides as a function of temperature, concentration, pressure, exposure time, and presence of other competing ions.

The experiments are quite simple. Small samples of deep-sea sediment are added to known volumes of artificial seawater, containing, in dissolved form, the element of interest. In each case, a tiny fraction of the element is a commercially available radioactive isotope. By measuring the radioactivity of the solution before and after it has equilibrated with the sediment, we can calculate the amount of the element sorbed by the sediment, and hence the distribution coefficient. In some cases, the sorption experiments are first carried out using a sodium chloride solution, rather than artificial seawater, so that we can distinguish reactions in the solution, such as the formation of insoluble salts, from sorption reactions. Figure 3 shows results from a series of experiments at 85 degrees Centigrade between thorium solutions in sodium chloride brine and surface sediment from the North Pacific. In this case, the weaker the thorium solution, the greater the proportion of the thorium sorbed onto the clay.

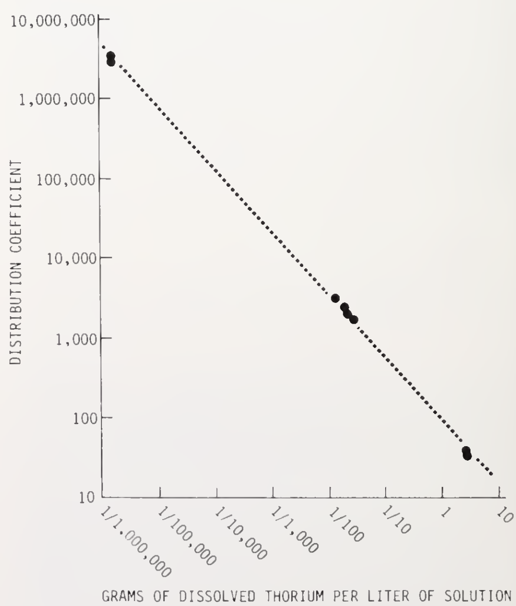

Figure 3. The lower the concentration of dissolved thorium, the greater the fraction bound to clay minerals. Thus, burial of waste elements in a highly insoluble form would greatly slow down their subsequent migration through the sediments.

Work by Egberg Duursma at the International Atomic Energy Agency laboratory in Monaco and preliminary results from our experiments suggest that for North Pacific clays, the

Table 1. Properties of high-level waste a year after separation from Light-Water Reactor fuel (1.4 years after removal from a reactor), compared to "throwaway" (unprocessed) fuel one and one thousand years after removal from a reactor.

Element	Radioactivity (curies per metric ton of heavy metals)		
	Waste	"Throwaway" Fuel 1 year	1000 years
Tritium	40	490	-
Selenium	-	3/10	3/10
Krypton	-	7,400	1/1,000,000
Rubidium	-	7/10,000	2/100,000
Strontium	54,000	70,000	1/1,000,000
Yttrium	55,000	79,000	1/1,000,000
Zirconium	6,400	35,000	2.3
Niobium	14,000	75,000	2.2
Tecnecium	11	11	11
Ruthenium	205,000	200,000	-
Rhodium	205,000	200,000	-
Palladium	-	7/100	7/100
Silver	20,000	20,000	-
Cadmium	25	23	-
Indium	-	4/100	-
Tin	320	640	4/10
Antimony	6,400	5,700	5/10
Tellurium	2,700	4,200	-
Iodine	-	24/1,000	24/1,000
Xenon	-	1/100,000	-
Cesium	180,000	200,000	3/10
Barium	77,000	77,000	8/1,000,000
Lanthanum	-	5/1,000	-
Cerium	310,000	480,000	2/100,000
Praseodymium	310,000	490,000	2/100,000
Neodymium	-	7/100,000	-
Promethium	80,000	87,000	-
Samarium	1,100	980	6/10
Europium	8,200	7,800	-
Gadolinium	-	5	-
Terbium	-	25	-
Uranium	4/100	3.2	2
Neptunium	140	6.5	6.3
Plutonium	1,500	71,000	660
Americium	780	170	530
Curium	380,000	3,500	1/10
Berkelium	-	8/100,000	-
Californium	-	3/1,000,000	-
Total	1,580,000	2,200,000	1,200

Note: After 10 years, the radiation level at 1 meter from this quantity of waste is 1.7 billion times the whole-body exposure level permitted by the Nuclear Regulatory Commission for people working with radioactive materials.

distribution coefficients for waste elements at low concentrations have values like 100 to 6000 for strontium 90, 1400 for cesium 137, 3000 to 20,000 for zinc 65, 140,000 for cerium 144, and 1,000,000 for thorium 228. Put another way, these figures indicate that in ten million years, the elements would diffuse over the following distances: strontium, 4 to 32 meters; cesium, 8 meters; zinc, 2 to 6 meters; cerium, 1 meter; and thorium, less than a third of a meter. These figures are in no way final estimates of waste migration in the seabed. They do, however, give a sense of the strong interaction between dissolved waste components and deep-sea sediments. Recent experiments suggest that these

figures are on the liberal side, so the actual barrier effect of the sediment may be even more impressive than it first appears. In particular, Duursma's studies show that distribution coefficients for natural clay-water systems that have existed for decades or centuries are greater than values measured in the laboratory for the same systems, suggesting that migration distances will be less than predicted from our experiments.

It seems that for an undisturbed system, deep-sea clays probably provide a satisfactory barrier to protect man from buried waste. We do, however, need to collect more information on the solutions formed by reactions between pore waters and wastes, and on the distribution coefficients for elements in such solutions.

In the case of undisturbed sediments, movement of the pore waters is much slower than diffusion of nonreactive elements. When we try to carry the arguments from an undisturbed system to a situation in which a hot canister has been forcibly inserted into the seabed, however, we become aware of the amount of study needed to assess the effectiveness of the sediment barrier after modification by the emplacement, heat, and radiation of the canister. In this real case, the hot canister may produce slow convection of the pore fluids, leading to faster-than-expected upward transport of the radionuclides. The physical disruption will not affect the sorption properties of the clays, but it may facilitate physical movement of the pore waters. This problem is being studied by Walter Schimmel and his associates at Sandia Laboratories and by Armand Silva at the University of Rhode Island (see page 31).

Finally, we know little of the effect of the increased temperature that would result from the burial of radioactive wastes either on distribution coefficients or on the diffusion of elements through sediments in general. Work in our laboratory has shown that a temperature increase from 15 to 85 degrees Centigrade roughly triples the distribution coefficient of thorium, thereby increasing the amount of thorium sorbed on the sediment. By increasing the barrier effect of the sediments, this change opposes the effect of any pore water movement. Much more experimental work is needed to determine whether all the radionuclides of environmental concern behave like thorium, and to decide whether the over-all effect of the disruption of the sediment during emplacement and of the heat produced by the wastes damages or reinforces the sediment barrier.

The gaps in our knowledge considerably exceed the facts in hand when it comes to deciding whether high-level radioactive wastes can be safely contained in the seabed of the deep oceans. Nevertheless, our findings to date are grounds for cautious optimism. We must now carry out experiments to determine the expected lifetime of a buried canister, the rate of leaching of waste material by pore waters, and the rate of movement of dissolved elements through the seabed. These will allow us to better assess the feasibility of high-level waste disposal in the geological formations beneath the oceans.

G. Ross Heath is an associate professor in the Graduate School of Oceanography at the University of Rhode Island, Narragansett.

Reference

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Physical Processes in Deep-Sea Clays

by Armand J. Silva

The fine-grained sediments that blanket portions of the ocean basins possess several characteristics that are favorable for the disposal of high-level radioactive wastes: 1) the sorption properties of the clays tend to inhibit the movement of dissolved radionuclides (see page 28); 2) the rate of water migration through the sediments is very slow compared to other geologic formations; 3) the strength of clays is generally very low — facilitating the emplacement of canisters; and 4) since the sediments are in a plastic state, they do not fracture if disturbed and tend to "heal" if disrupted. The primary force for water migration comes from the heat generated by the waste container. Therefore, it is important to understand the physical interactions between the canister and surrounding sediment so that the long-term dispersal of waste materials can be predicted.

Assumptions — Problems

Our studies to date have been based on certain assumptions regarding the form of the waste (see page 26), and the state of technology of delivery systems. These include:

The Waste Form

Radioactive material will be converted into a solid glass of relatively low leachability.

The Canister

Present plans call for use of a corrosion-resistant metal. Initial studies presume a cylindrical shape approximately 30 centimeters in diameter (1 foot) by 3 meters long (10 feet). It is assumed that the canister will develop cracks or leaks after a few hundred years.

The Radioactivity

The level of radioactivity and rate of decay of the full suite of elements is such that the waste elements must not be allowed to escape from the seabed for a million years.

The Heat

The heat generated by a freshly filled 3 meter canister is approximately 1 to 10 kilowatts, or roughly equivalent to that produced by 10 to 100 reading lights. However, the canisters can be stored temporarily, allowing them to cool before emplacement.

The Emplacement Technology

It is assumed that if a suitable barrier exists, present technology can be adapted for efficient delivery of waste canisters to depths of tens of meters into the sediments or, if necessary, into underlying rock formations.

* * *

There are several challenging problems associated with the use of deep-sea clays as a repository for high-level waste or as an added barrier if the canisters are placed in underlying rock formations.

The Radioactivity Problem

The sediment cover must: 1) provide enough mass between the canister and the water column to ensure that living organisms will not be contaminated by radioactivity, and, 2) ensure that the migration through the medium will be low enough to allow dissipation of radioactivity before reaching the sea floor.

The Heat Problem

The heat generated by waste a year after removal from a reactor is high (approximately 8 kilowatts per ton of heavy metal processed) but decays to approximately 0.5 kilowatts per ton after 30 years. However, even if the waste is allowed to cool for a number of years, the temperature buildup, if the canisters are in a poorly conducting material (such as deep-sea clay), will be considerable. The basic questions are: 1) will cooling take place by

conduction, or will convection (circulation) play an important role (convection could take place either by movement of only the pore water of the sediments or by fluidization of the entire sediment/pore water system); and 2) will the change in temperature alter the chemical characteristics of the sediment, cause significant pressure gradients to be set up, or otherwise modify the disposal environment?

The Water Migration Problem

Clay sediments in the deep sea are saturated with seawater and typically have high porosities (usually, more than 50 percent of the total volume is water). However, the resistance to water flowing through the clays is very high (or, alternatively, the permeability is very low). The rate of water migration is controlled primarily by two factors: 1) the permeability of the sediment, which is essentially a constant for a given clay, and; 2) the pressure gradient (the velocity of water is directly proportional to the gradient). This pressure gradient can arise from physical (stresses), thermal, and chemical factors. Existing natural gradients due to overburden stresses (compaction), cyclical water pressures, etc., must be taken into account but are very small. Of greater concern are gradients produced by a concentrated heat source, such as a waste canister. Such thermal gradients may well produce an upward flow of pore water away from the waste canister that tends to carry radionuclides toward the sea floor.

The Penetration Problem

If the canister is to be pushed into the sediment, the driving energy must be sufficient to overcome the strength of the clays. Any emplacement plan entails disruption of the sediment, which will affect its physical properties. In addition, any cavities created by emplacement procedures must be adequately sealed to prevent rapid migration of wastes back up into the ocean.

Geotechnical Properties of Sediments

Information on the physical properties of sediments provides part of the data base necessary for long-term prediction of the behavior of potential repository sites. A combination of spot sampling by coring or drilling and sub-bottom acoustic profiling techniques are used in these studies. So far, we have looked at deep-sea clays generically without becoming very specific about site investigations.

Two areas in the Pacific, about 600 miles and 800 miles north of Hawaii, were selected for initial studies, but the methodology used is equally applicable to any potential disposal site. Typical profiles of water contents at the two Pacific sites are illustrated in Figures 1 and 2. Both of these profiles show an upper zone (5 meters thick in Figure 1 and 2 meters thick in Figure 2) of constant water content (and constant density) and gradual increases to very high water contents of approximately 240 percent near the bottom of each core. These unusual increases — a decrease in water content and increase in density with depth due to overburden stresses is more common — are due to a change of mineralogy from illite-rich clay in the surficial layers to smectite-rich clay at greater depths.* The constancy of water content within the upper illitic clays is attributed to high interparticle bonding forces within

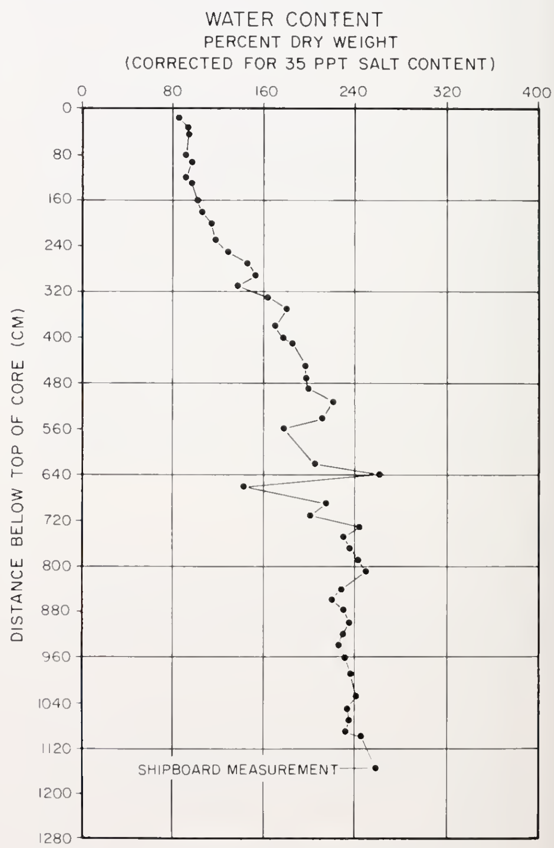

Figure 1. Water content profile in core taken 600 miles north of Hawaii at 31°-05.0'N, 158°-31.0'W (study site MPG-1). Note almost constant water content (and density) in upper five meters of illitic clay and steady increase of water content caused by a transition to smectite-rich material. The smectite is much more fine grained than the illite.

**Illite is a common clay mineral with a platy (flaky) structure similar to that of mica, having moderate potential for adsorbing ions. Smectite clays are characterized as being platy shaped, extremely fine grained, very plastic, with high potential for sorbing ions. Bentonite or "drilling mud" is a smectite.*

the sediment fabric that tend to inhibit the natural compaction process. A typical scanning electron micrography of an undisturbed illitic clay is shown in Figure 3. The fineness of the deeper clays can be visualized by realizing that the particles in six grams of smectite (a penny weighs three grams) have a combined surface area equal to that of a football field.

Until recently the longest core taken in the Pacific study areas was about 10 meters. In order to extend our knowledge to greater sediment depths, a research cruise was undertaken on the *C/S Long Lines*, a cable-laying ship, in October, 1976. During this expedition, a large diameter, 7.5 ton corer

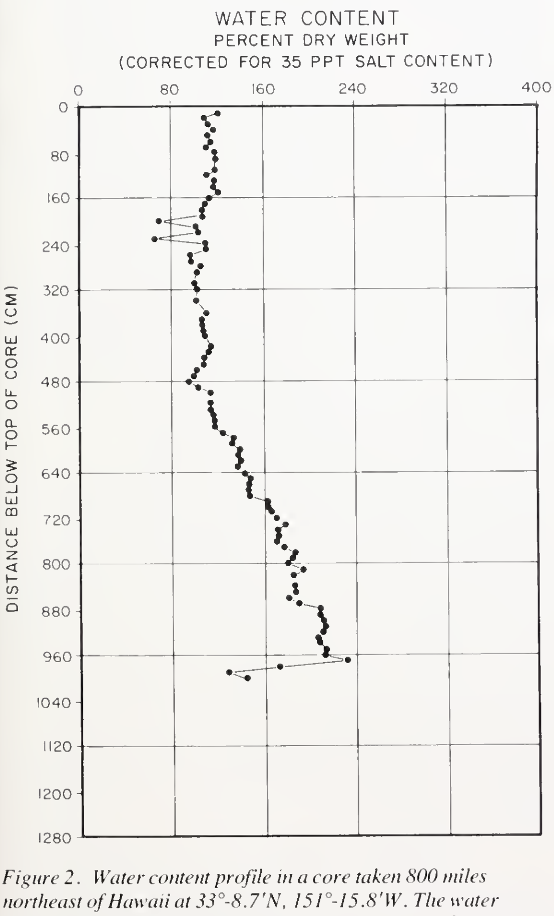

Figure 2. Water content profile in a core taken 800 miles northeast of Hawaii at 33°-8.7'N, 151°-15.8'W. The water content is nearly constant in the upper 1.6 meters and increases dramatically to over 240 percent in the lower zones where the clay changes from illite-rich to smectite-rich.

(Giant Piston Corer) was used to obtain a 24.4 meter core in the Pacific study area (Figure 4). This core is undergoing extensive analysis and therefore only preliminary data are available at this time. A plot of strength versus depth (Figure 5) shows that the shear strength is over 300 grams per square centimeter at a

5 Microns

Figure 3. Typical scanning electron micrograph of the internal "fabric" of an illitic clay showing open "card house" structure of flat particles with large voids that are filled with sea water in the natural condition. The electro-chemical surface characteristics of the particles produce a net attraction to water molecules thus decreasing the mobility of the pore fluid and resulting in a matrix of low permeability.

24 meter depth. Although this is not an extremely high strength, it does indicate that penetrations greater than 25 meters in this area would require larger driving forces or other means of overcoming the sediment strength, such as drilling, jetting, or vibratory coring. Except for occasional thin (1 to 5 centimeter) layers of altered volcanic ash and one layer impregnated with ferromanganese hydroxides at a 10 meter depth, the sediment at this core site appears to consist of an upper 4 meter zone of brown illitic clay followed by a transition to dark reddish-brown smectite-rich clay that is quite uniform to the bottom of the core.

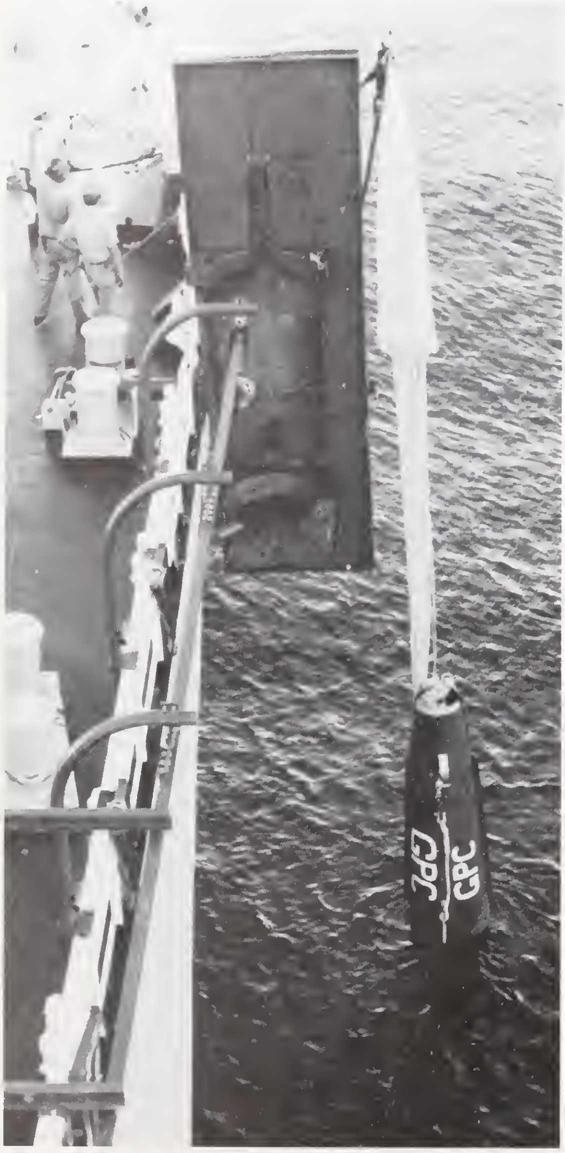

Figure 4. Giant Piston Corer (15,000 pounds) being launched from the C/S Long Lines. *Note rotating weight stand platform in vertical orientation and handling system (rails, brackets, etc.) installed on ship especially for this coring operation. Only a few large ships can launch and retrieve the large diameter (11.4 centimeters) corer in deep water.*

We have begun laboratory experiments to determine the permeability characteristics of these deep-sea clays. Typical results for a sample of illitic clay are shown in Figure 6. This graph shows that the permeability decreases with decreasing void space (void ratio is the volume of voids divided by volume of solids). Most of the test results indicate that for a hydraulic gradient of unity (hydraulic gradient is a measure of rate of pressure loss when flow occurs) water will migrate through the sediment at 10^{-8} to 10^{-7} centimeters per second or approximately 3 to 30 centimeters a year. The actual hydraulic gradient due to thermal effects will be much smaller than unity and, therefore, the rate of water migration will be much slower. It should be remembered that the effectiveness of the sediment as a barrier is also dependent on other properties, such as ion sorption (see page 28), kinematic dispersion, and molecular diffusion.

Thermal Effects

Understanding the response of sediments to the heat generated by a waste container is perhaps the most complex problem we face and one that is being studied from several points of view. Existing theory is being used by W. P. Schimmel of Sandia Laboratories, a government research complex in New Mexico, to mathematically model and thereby predict the temperature and flow fields around a heat source within the sediment. In addition, we have begun laboratory and field experiments to test the theoretical predictions and gather more data. The question of whether the canisters will be cooled by convection or conduction is far from trivial because the very low permeability of the saturated clays and the low interstitial water velocities involved require highly sophisticated measurements.

Studies to date indicate that the temperatures around a canister will be approximately those predicted for a heat source in a conducting medium. Since the thermal conductivity of the clays is quite low (bricks made of clay are good insulators), fairly high temperatures will build up near the canisters (over 200 degrees Centigrade). Thus, substantial thermal gradients will exist around each container (Figure 7). These temperature gradients will give rise to hydraulic gradients that in turn will cause water to migrate outward from the heat source (Figure 7). Because the temperature decreases and the flow field expands, however, the hydraulic gradient diminishes rapidly with distance from the canister.

Fortunately, the radioactive elements that produce most of the heat have short half-lives, so that the waste will lose essentially all its thermal energy after a few hundred years. Thus, containment of the radioactive elements by the glass waste and by the canister, combined with the fact that the permeability of the clays is very low, should minimize any dispersion of radioactive elements due to thermal effects during the first one to two centuries after burial.

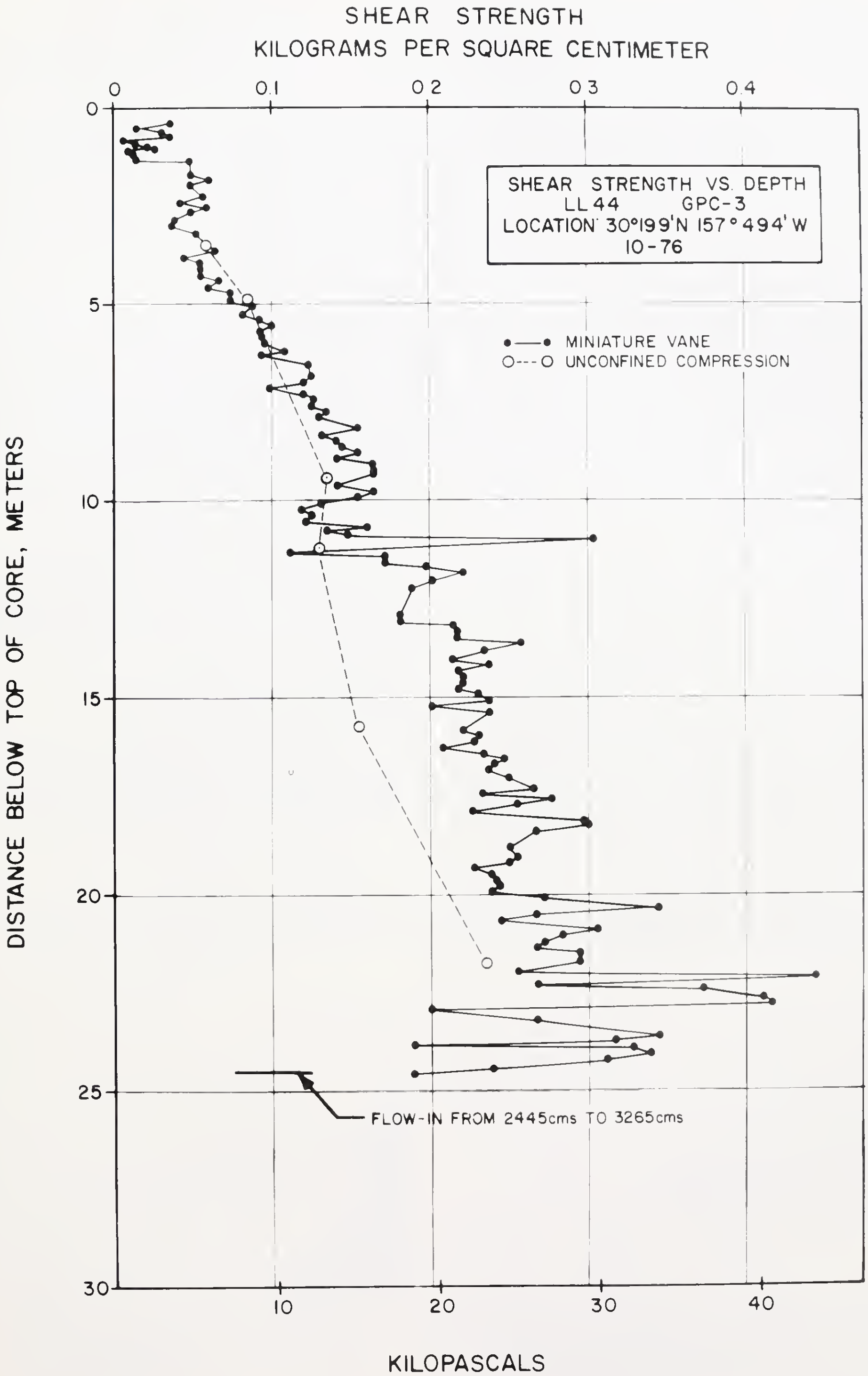

Figure 5. Shear strength profile in a core taken with the large diameter piston corer (Giant Piston Corer) 600 miles north of Hawaii. Shear strengths were measured on board ship soon after recovery of core. The measurements show an upper 4-meter zone with essentially constant strength and then a gradual increase in shear strength with depth, but at a diminishing rate of increase. This information could be used to predict the depth of penetration of emplacement devices.

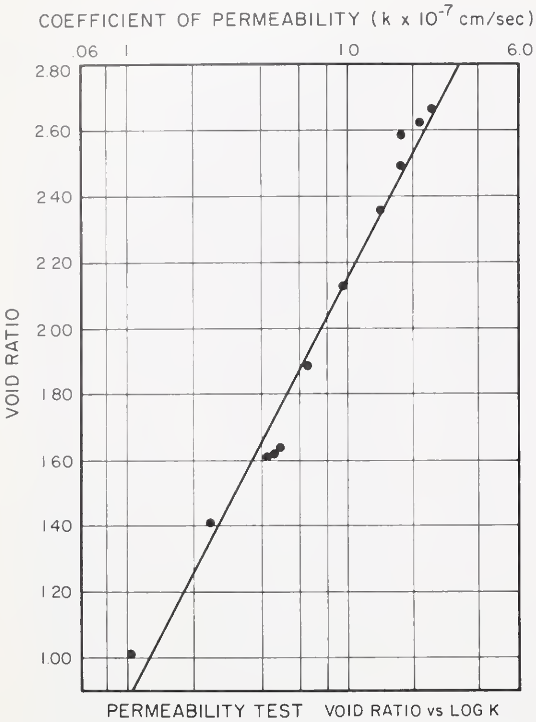

Figure 6. Results of laboratory permeability tests conducted on an illitic clay. Void ratio is the volume of voids divided by volume of solid particles in a given sediment space. Coefficient of permeability is the velocity of water migration produced by a unit hydraulic gradient (change in pressure head divided by length of drainage path).

Emplacement Techniques

Possible methods of placing canisters at the proper depth in a sediment or rock layer range from controlled drilling by a surface ship or bottom-crawling apparatus to a streamlined projectile falling through the water column. The untethered, free-falling penetrometer approach appeals because it is simple, but the full spectrum of possible techniques will have to be studied before a total delivery system can be designed. In a sense, it is premature to enter into a detailed analysis and design of emplacement techniques before we know whether the seabed disposal concept is feasible. On the other hand, procedures should at least be considered in a preliminary fashion in order to assess their effects on the sedimentary barrier. In this assessment, however, we are considering only technology that is currently available (with some modifications and refinements).

The first three concepts that follow are shown in Figure 8. Cost comparisons also are included, but not discussed, although this probably would not be the deciding factor in selecting an emplacement technique.

Projectile Emplacement

The streamlined waste container would be dropped from a ship through the water column. A terminal velocity of more than 30 meters per second

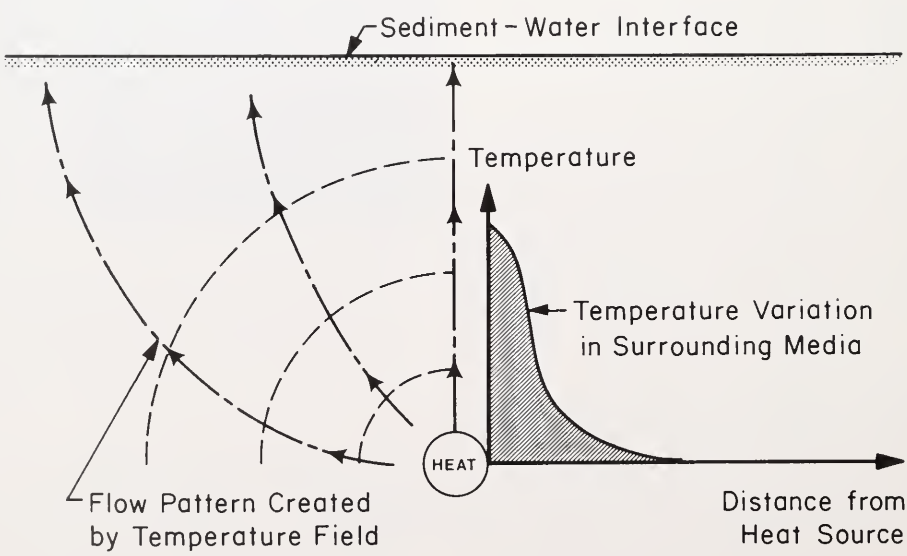

Figure 7. Temperature variation and flow field caused by a heat source in a relatively impervious but saturated porous media such as clay. The bell shaped curve on the right side shows the rapid decrease in temperature on a horizontal plane beginning at the canister wall. The lines on the left radiating out from the source illustrate the flow of water generated by the heat field in the sediment surrounding the canister. (Adapted from W. P. Schimmel and C. Hickox)

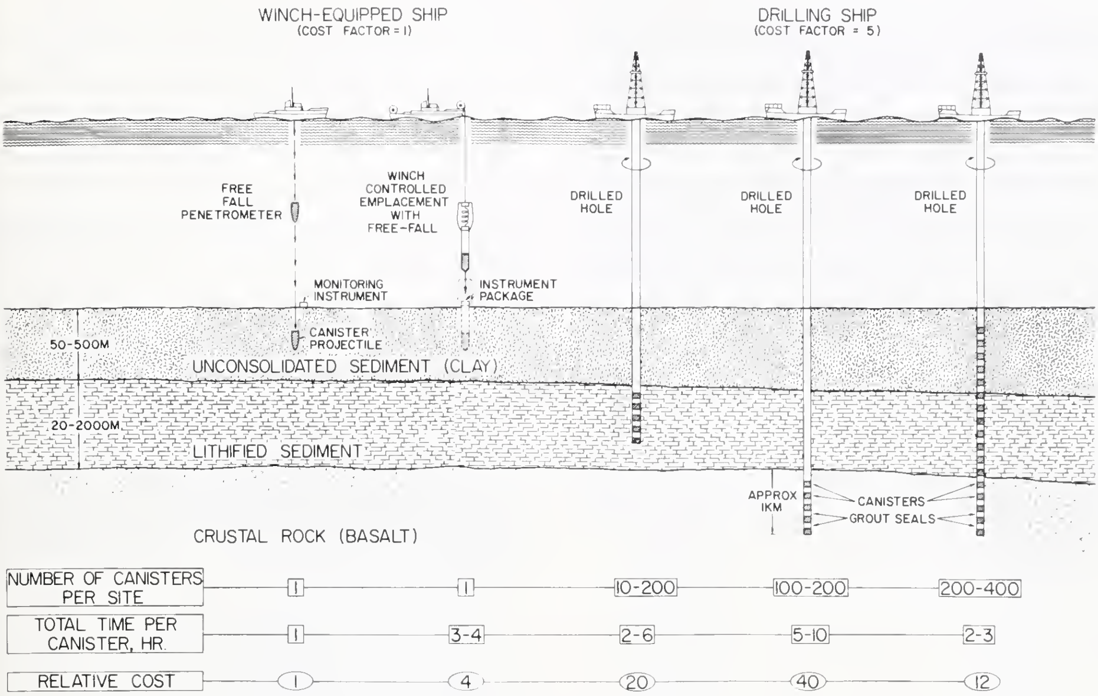

Figure 8. Engineering concepts for emplacement of radioactive waste canisters in the seabed.

(approximately 70 miles per hour) would be reached before the canister began to penetrate the soft sediments. Depending on the sediment strength characteristics, we expect that penetration could exceed 30 meters. The penetrating projectile would rupture the sedimentary material. However, laboratory studies indicate that closure would occur immediately behind the falling canister.

Winch-Controlled Emplacement

In this option, the waste canister would be attached to the bottom of a device designed to penetrate into the sediment, using either its momentum (similar to a piston corer), or some other driving mechanism, such as vibration or jetting. The waste container would be released before withdrawal of the emplacement device but only after it had been determined that the proper depth of penetration had been attained. One advantage of this method is that the canister could be recovered in the event of a malfunction. If necessary, it would be possible to provide a sealant (perhaps of the same clay) that could be left to fill the cavity above the canister as the device is pulled out.

Drilled Hole

The technology for deep-sea drilling from a surface ship has been developed by the Deep-Sea Drilling Project, a joint effort by several marine research centers. This emplacement technique has the advantage that many canisters could be placed in a single drilled hole, probably with a sealant between canisters. Such drilling probably will be necessary if burial depths greater than about 50 meters are needed to provide an adequate barrier.

Other Concepts

Additional procedures that are intriguing but require more study involve the use of remotely controlled or manned bottom-crawling equipment to bury waste packages. If the required sediment cover does not exceed a few meters, it might even be possible to place the waste in a continuously excavated trench (that could then be backfilled) much in the same fashion as modern pipelaying operations on land.

Hole Closure Problem

As previously mentioned, any emplacement procedure will necessarily disrupt the sedimentary layer. In order to prevent "short-circuiting" of the barrier, it is essential that the cavity created by the emplacing device be filled — either with the same type of sediment or with a suitable sealant. Thus, it is important to know the behavior of the sediment during and subsequent to penetration.

Figure 9. Test frame for laboratory experiments to study hole closure behavior of sediments when subjected to dynamic and static (slow) modes of canister emplacement. Before penetration, the homogenized sediment in the tank (51 centimeter diameter) is consolidated to a predetermined stress level to simulate natural overburden conditions.

As a first step in studying the complex problem of "hole closure," we have carried out a series of laboratory simulation experiments. Results of these preliminary studies are being used to design additional laboratory and in-situ experiments as well as to give direction to theoretical analyses. The experiments have included penetration by high-velocity projectiles fired from a compressed air gun and by a penetrometer pushed in at a relatively slow rate (approximately 10 centimeters per second).

For each experiment, a completely homogenized and saturated sediment was consolidated in a tank (51 centimeters in diameter by 107 centimeters high) to a stress corresponding to in-situ overburden conditions at the depth to be studied. The tank was then transferred to a test frame (Figure 9), the consolidating stress reapplied and the penetration tests (two dynamic and two static) carried out. The configurations of cavities left in the wake of the projectile were preserved by pouring in a quick setting epoxy resin 1 hour and 24 hours after the emplacements.

Two distinct closure patterns have been observed in the 12 penetration tests completed to date (three different overburden stress conditions were simulated — 10 meters, 19 meters, and 28 meters). Except for a small cavity near the surface due to cratering, all the dynamic tests were followed by immediate and total closure of the hole (Figure 10). In contrast, the static (slow) penetration tests were not followed by immediate closure. Instead, the walls of the cavity (Figure 11) flowed gradually inward with the softer (upper) sediments closing at a faster rate than the stiffer materials at greater depth. It may be possible, however, to modify the static penetration/withdrawal device so as to force closure from deeper to shallower depths (perhaps by taking advantage of natural suction pressures).

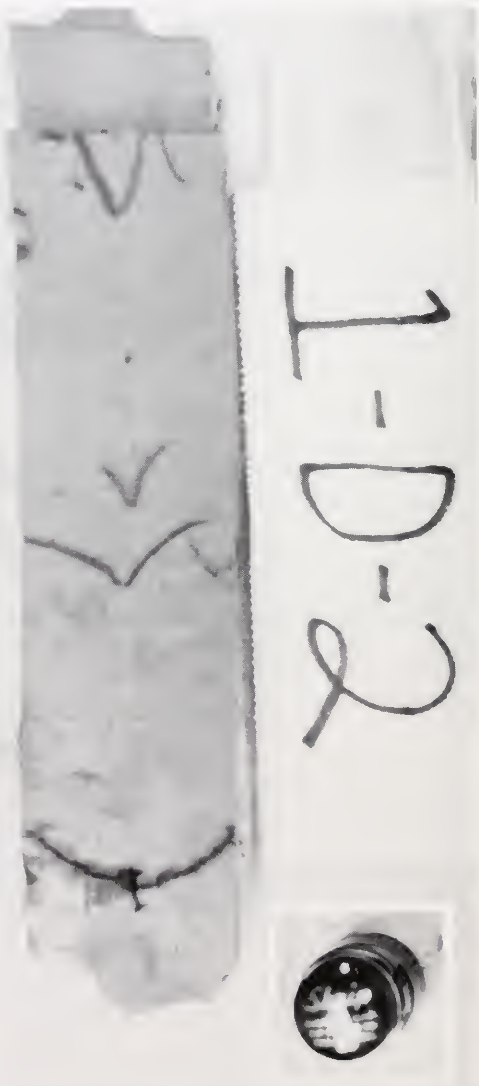

Figure 10. Typical appearance of sediment after dynamic penetration of a projectile. The hole has closed immediately and completely. Distortion of the sediment in the wake of the projectile is shown by the highlighted layers that were originally horizontal.

These initial experiments suggest that closure of a completely penetrating projectile would be immediate and total, but closure of a hole left open by an emplacement rod would be gradual.

Emplacement in Rock

Disposal in the deeper lithified sediments (greater than 500 meters, where material is no longer plastic) is also being considered. Owing to higher shear strength and reduced plastic properties, these sediments are susceptible to fracturing that could lead to fast migration of fluids along cracks. The transition downward from soft to lithified deposits may be gradual or abrupt, and sometimes alternating layers of unlithified and lithified sediments are found. Our knowledge of the variation of lithification at depths of more than 30 meters below the sea floor comes mainly from Deep-Sea Drilling Project holes.

Disposal within the igneous oceanic basement beneath the sediments also has been considered but has not been pursued to the same extent as the sediment studies. To date only a few holes have been drilled 500 meters or more into basement by the Deep-Sea Drilling Project. The emerging picture is that the basement has great lateral inhomogeneity, comprising: 1) a layer of basaltic pillow lavas (resulting from underwater eruption and rapid chilling of molten lava), fractured blocks and breccia, sediment-filled cavities, and inter-layered sediments overlying and invaded by quantities of basalt, grading down to 2) basaltic dykes — more massive than pillow lava but with numerous vertical contact boundaries of variable properties — overlying at depths of several kilometers, and 3) more massive horizontally layered gabbros and related rocks.

The whole basement complex is cut by fractures and fissures to depths of 100 meters or more. Ocean water circulated through these cracks while the rock was cooling during crustal formation and circulation may continue to this day. This has resulted in extensive alteration of the basalts and the development of secondary mineralization. Because the nature of the igneous basement is poorly known and unpredictable, neither it nor the overlying lithified sediments appear to warrant serious consideration as disposal sites at the present time.

Additional Problems

Several interesting problems concerning the

Figure 11. Sketch of hole profiles in a homogeneous sediment after slow rate of penetration (10 centimeters per second) of a projectile. The profile on the left was taken 1 hour after test, and the one on the right 24 hours. Note the continuing closure with time that indicates gradual creep or flow of the walls due to overburden stress.

sediment are still outstanding. Some of the more intriguing:

Mass Fluidization

There is a possibility that the material immediately adjacent to the canister may be transformed into a viscous fluid due to convection. This situation could result in the canister sinking through the sediment column (assuming it is denser than the surrounding fluidized material). The conditions under which this process might take place cannot be predicted from present knowledge.

High-Temperature Alterations

Very little is known about how the physical and chemical properties of the sediments are modified by a thermal gradient under pressure — the pressure due to depth of water exceeds 500 atmospheres (10,000 psi) over most of the deep-sea floor.

Aquifers

Continuous layers of highly permeable sediments within the clay formations could provide pathways for quick lateral migration of pore water, with eventual release at outcroppings that could be far from an actual containment site. Detailed core sampling and seismic studies of potential disposal sites can assure that such layers are absent.

* * *

At this stage of the program, we do not know whether the unlithified sediments of the deep seabed form an effective barrier to contain high-level wastes. However, we have not been able to uncover data that disqualify soft, fine-grained deep-sea clay as a potential disposal medium for radioactive wastes. If future studies support this conclusion, we will then conduct exhaustive field studies at specific potential disposal sites to assure that the local geologic conditions are adequate to contain the wastes until they have decayed to harmless by-products.

Armand J. Silva is a professor of Ocean and Civil Engineering at the University of Rhode Island, Kingston.

Suggested Readings

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ABYSSAL COMMUNITIES AND RADIOACTIVE WASTE DISPOSAL

by Robert R. Hessler and Peter A. Jumars

The value of nuclear power always has been diminished by the specter of adverse side effects. Most of the delay in its utilization stems from our concern about safety. We are concerned about potential environmental damage and about hazard to man. Today, of course, it is recognized that these can be at best only imperfectly separated from one another; mankind is firmly enmeshed in the environmental network. Since our primary concern is with the biological side effects, it follows that in searching for an adequate place to dispose of radioactive wastes, the task is to isolate the wastes from biological systems. If some portion of the biosphere might potentially be exposed, then it is desirable that the biological pathways leading back to man be as few and as tenuous as possible. One of the initial incentives for studying the possibility of burying wastes in the sediment under the deep-sea floor of central oceanic gyres was the hypothesis that the communities here fulfilled these criteria.

Food for deep-sea bottom communities ultimately comes from above, through the chain beginning with primary productivity at the sunlit surface (Figure 1, A). In the central gyre waters such production is low. Furthermore, prevailing oceanic currents as well as remoteness from land preclude any significant terrestrial contribution. These factors, combined with the great water depth, result in a lower nutrient supply to the bottom than can be found at any other place in the ocean. Here the standing crop is extremely sparse. In the macrofauna (generally, the larger animals retained on a sieve with 0.3 millimeter openings), there are only about 85 to 160 individuals per square meter, or about

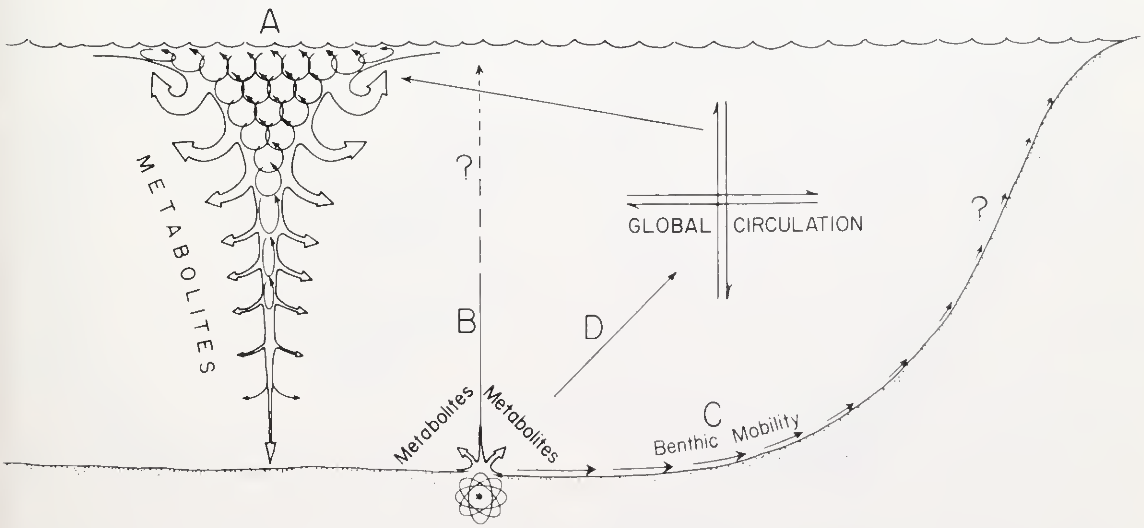

Figure 1. Diagram of the position of deep-sea benthic communities within the biosphere. The downward-pointing arrow, A, represents the attenuated downward flow of nutrients through the pelagic ecosystem. The converse arrow, B, represents much smaller return flow. Radioactive substances incorporated into the benthic community might be spread via B, benthic mobility C, or mass transport of metabolites D.

0.02-0.05 gram wet weight per square meter. This is two to three orders of magnitude lower than in shallow coastal waters.

These data lead us to conclude that the organic activity per unit area is relatively lower in the deep sea than in shallow water (Figure 2). However, the activity of this community is probably even lower than the standing crop suggests. While only a handful of measurements of deep-sea community metabolism have been made, and none in these particular parts of the ocean, they suggest that the pace of life in the deep sea is much slower than in shallower waters.

Respiration of the total community as measured in situ by oxygen utilization of a piece of bottom is the best summary measurement available for general community activity. Oxygen uptake per unit biomass appears to be about an order of magnitude lower in the abyss than in shallow water (K. L. Smith, Jr., in manuscript). Fish from 1200 meters respire many times more slowly per unit body weight than do related shallow-water fish (Smith and Hessler, 1974). Carefully controlled experiments of nutrient uptake by bacteria have revealed extraordinarily low free-living bacterial activity in the deep sea (Jannasch and Wirsen, 1973). This stands in strong contrast to the condition in shallow water, where bacterial activity is intense. Radium-thorium dating of the shell of a deep-sea bivalve (*Tindaria calistiformis*) demonstrated that individuals could be as old as a century and that reproductive maturity is attained only after about 50 years (Turekian et al., 1975). Another bivalve study revealed more rapid development, but *Tindaria* gives indication of the kind of slow rates that can be achieved in the deep sea. In aggregate, all these data indicate that what life there is in the deep sea acts on its chemical milieu at minimal rates. If such a community were exposed to radionuclides, it should cycle them much more slowly than other oceanic communities.

What are the organisms that form this deep-sea community? Contrary to uninformed suspicions, the composition is not basically different from that of shallow-water mud bottoms (Table 1). Polychaete worms, bivalve molluscs, peracarid crustaceans (closely related to pillbugs and beach hoppers), Foraminifera, nematodes, and harpacticoid copepods dominate the fauna.

These are the creatures captured in grab, core, and dredge samples (Figure 3). The larger, more mobile organisms can avoid such samplers. For this reason, they have only recently been given the consideration they deserve. The employment of

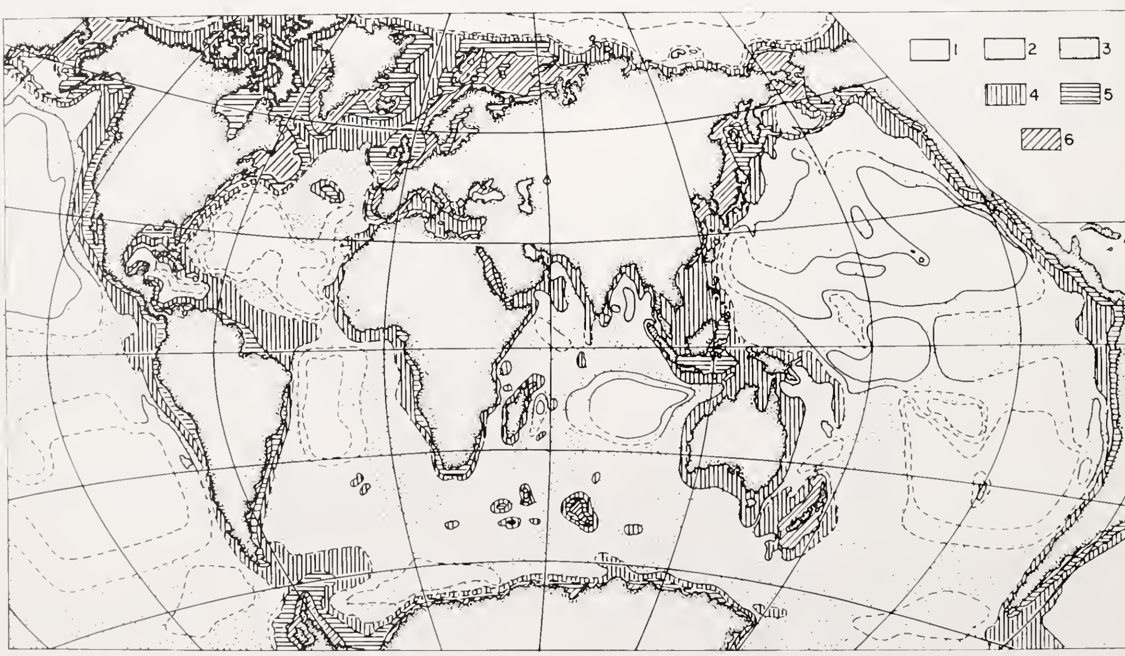

Figure 2. Distribution of benthic biomass (wet weight) of the world's oceans (modified from Belyayev et al., 1973). This map is conceptually correct, but in view of the small number of quantitative samples that have been taken in the deep sea, much of it must be regarded as an extrapolation. The areas of lowest biomass reside under central oceanic gyres and contain the sites that, from a biological point of view, are likely to be most suitable for radionuclide waste disposal. Symbols: 1, <0.05; 2, 0.05-0.1; 3, 0.1-1.0; 4, 1.0-10.0; 5, 10.0-50.0; 6, 50.0->1000.0. Units are in grams per square meter.

Table 1. Faunal composition (in percent of total macrofauna) of abyssal benthic gyre communities under the Sargasso Sea in the western North Atlantic (Sanders, Hessler, and Hampson, 1965), and under the central North Pacific (Hessler and Jumars, 1974).

	Northwest Atlantic > 4000 m	Central North Pacific 5600 m
Porifera	0.2	1.1
Cnidaria	0.5	1.4
Polychaeta	55.0	55.1
Oligochaeta	—	2.1
Sipunculida	4.5	0.4
Echiurida	—	0.4
Priapuloidea, Nemertina, Pogonophora	0.6	—
Tanaidacea	19.2	18.4
Isopoda	12.1	6.0
Amphipoda	1.5	—
Cumacea, Misc. Arthropoda	0.2	—
Aplacophora	0.3	0.4
Bivalvia	4.2	7.1
Gastropoda	0.6	0.4
Scaphopoda	0.2	2.5
Ophiuroidea	0.8	0.7
Echinoidea	0.2	—
Asteroidea, Crinoidea, Holothuroidea	—	0.4
Bryozoa	—	2.0
Brachiopoda	—	0.7
Ascidiacea	—	1.1

traps, baited cameras, and submersibles has demonstrated that, even in the sparse abyssal community on the bottom of food-poor gyres, fish play a significant role, as do highly mobile scavenging amphipod crustaceans (Figure 4). The relative abundance of these creatures is still not known because of the difficulty in quantifying the observational techniques.

The degree of difference in faunal composition between shallow-water and deep-sea soft bottoms depends on the taxonomic level being considered. As previously mentioned, at higher levels they are the same — polychaetes, nematodes, fish, etc. However, at lower levels differences become apparent. There are orders that are far more abundant in the deep sea. Many families and to a greater extent genera are essentially limited to that realm. The species are different from those in shallow water with few exceptions.

In terms of horizontal distribution within the deep sea, taxonomic groups are very widespread. Even genera tend to be cosmopolitan. Individual species, however, usually have more restricted distributions and may frequently be confined to a single basin.

These relationships are relevant to the issue of radioactive waste disposal. The broad distribution of the community, which includes the localities of potential disposal sites, ensures that the mechanical side effects of disposal or small-scale leakage will affect only a small fraction of the total area covered by the community. Disturbance of a small area is thus unlikely to entail the risk of extinction for any of the myriad deep-sea species. (The ocean abyss is so huge that even hundreds of square kilometers qualify as a "small" area.) Disturbance of *many* small areas or of any large one is clearly another matter. Consideration of the high diversity and low standing crop shows that individual species exist at extremely low abundances. A wealth of ecological theory predicts that any significant perturbation of populations at such low abundances will lead to extinctions.

One of the most surprising discoveries of the last decade of deep-sea research was that, contrary to previous belief, deep-sea communities contain a very large variety of species. This high diversity is similar to that found in the shallow-water tropics and is much higher than that of similar bottoms of shallow temperate or boreal regimes. This would seem to be paradoxical in view of the apparent rigor of deep-sea environments — near-freezing temperature, absence of sunlight, and extremely low food levels. However, such an

Figure 3. The fauna found in 0.25 square meters of bottom at 5597 meters in the central North Pacific (Station H-153: 28°25.91'N, 155°30.05'W). All of the animals are much smaller than depicted here, such that if they were in true proportion to the square, one would see nothing.

environment is rigorous only to an organism that is not adapted to it. Outweighing the apparently extreme nature of all these features is the constancy of the deep-sea environment under oceanic gyres: temperature, salinity, oxygen, and the sedimentation rate are essentially unvarying. Currents are modest by shallow-water standards. There are no major storms. What food comes in from above probably does so at a fairly constant rate. Such stability minimizes the likelihood of extinctions even for species maintaining extremely low population densities, and thereby allows the diversity of communities to build to high levels. This indicates that the amount of available food is subsidiary to environmental stability in determining species diversity.

While no one has yet measured the tolerances of abyssal organisms, it is almost a certainty that they can adjust to only a small degree of environmental change. This prediction is based on the general body of observation that selective pressure does not cause evolutionary adaptation to conditions to which a species is not exposed. This leads to the hypothesis that deep-sea communities are likely to be very sensitive to even small unnatural environmental perturbations. Thus, any kind of human activity on the deep-sea floor — be it waste disposal, nodule mining, or anything else — is likely to have a far more deleterious effect than would a comparable disturbance in shallow water. Furthermore, the slow rate at which deep-sea organisms conduct their lives combines with their sensitivity to make it likely that the community will recover very slowly from any disturbance. For this reason, the often used likening of the deep sea under gyres to a desert is doubly apt; not only is life sparse in the deep sea, but as in the desert, it is probably also very fragile.

We have yet to consider the place of this community within the total marine biosphere. Is it a dead end in the biotic web, or simply an intermediate in the continuous recycling of substances? The answer is apparently twofold: this benthic community is more or less an endpoint for particulate organic matter, but only an intermediary in the cycling of those materials that can be solubilized.

A fraction of the organic substances produced throughout the world continuously works its way into the abyss to form the food source for deep-sea organisms. The gradient of abundance of this material, both living and dead, is an exponential decrease from the surface downward. For this reason, because the deep sea contains only consumers, and because of gravity, the net flow of particulate organic material is downward (Figure 1, A). But, in the deep sea as in shallow water, there are swimming organisms that do consume benthic creatures, living or dead; the trap and camera studies of fish and amphipods show this. They provide one obvious mechanism for transferring materials back into the water column (Figure 1, B). For example, deep-bottom fish have been caught in midwater

Figure 4. Mobile scavengers attracted to bait in the central South Pacific (18°37'S, 141°18'W) at a depth of 4078 meters. The biotic conditions here of low nutrient input with resulting low benthic standing crop are those that typify the mid-plate, mid-gyre regions under consideration. The photo shows the three major types of fish scavengers: a macrourid (swimming, center), brotulid (swimming, behind the macrourid), and what is probably a zoarcid (resting on bottom). The white specks in the water are numerous amphipods, and the light dash in the distant background toward the upper left is probably a shrimp.

trawlings. So, while the gradient is against it, some material could work its way up to the surface. Still, this must be a miniscule fraction of what is moving downward. In this sense, the deep benthos constitutes nearly a trophic endpoint. There is also significant lateral transport within deep-sea communities. Animals walk, fish swim, and larvae drift with the currents. A molecule may move laterally until it works its way to the edge of the ocean basin and even up into shallow water (Figure 1, C). For example, several fish and crab populations of commercial interest make extensive seasonal migrations in bathyal depths (200 to 3000 meters). However, this too is probably not a major pathway for return of substances to shallow water.

Why then is no large concentration of deposited organic matter accumulating under the central oceanic gyres? Albeit slow, the pace of life is sufficient to utilize the small influx of organic material and to return nearly all of it to the overlying waters in remineralized form (nitrogenous wastes, phosphates, carbon dioxide, water, etc.), eventually to be incorporated once more into primary production. On a global basis, however, the majority of primary production is consumed and remineralized outside the central oceanic gyres. Even complete elimination of the benthic gyre communities might not exert any appreciable effect on the world's nutrient cycles.

So far, it might be argued that the potential benefits of deep-sea disposal outweigh the seemingly trivial or esoteric damage it might do. To politely paraphrase a colleague (working in the field of primary productivity), would the man on the street ever know or care if we paved the entire deep-sea bottom under gyres? The answer may be that perhaps the greatest general danger of deep-sea disposal of radioactive wastes comes not from the potential effects of accidentally leaked wastes on the community, but rather from the community's action on the wastes.

Two activities of animals in soft-bottom communities would pose a threat if any high-level radioactive wastes were to escape near the sediment surface. Animals move sediments, and animals move water into and out of the bottom as a normal result of their daily activities. Although many macrofaunal species feed within the sediments (at least down to 18 centimeters in the sediments beneath the central North Pacific gyre), the great majority deposit their solid wastes at or very near the sediment surface. An advantageous effect of this activity is that potentially noxious materials lying on the surface will be buried. On the other hand, sediments that would otherwise be exposed to the overlying waters only once in the sequence of deposition are brought to the surface several times before final burial in the mud below the maximal depth of animal activity. Redoubling this exposure of sediments to overlying water are animal

respiratory activities, including the irrigation of tubes and burrows with seawater. This pattern of movement of sediments and water as well as the metabolic activities of animals can be expected to put into solution and suspension many substances that would otherwise remain on or in the bottom. Radionuclides are among those substances. Once a substance is dissolved in the abyssal circulation, there is no part of the world ocean it cannot reach.

In summary, a waste disposal program involving the abyssal bottom under oligotrophic central gyre waters would come into direct contact with the most sparsely settled fauna on the face of the planet, and one which is very widely distributed. Compared to other members of the marine biosphere, this community occupies a relatively isolated position. In these terms, this would appear to be the most suitable place in the ocean for waste disposal. On the other hand, the fauna is likely to be sensitive to minor environmental perturbations, and would require a very long time to recover. Nor is its isolation so complete as to preclude the possibility of biological transfer of harmful substances if radionuclide leakage were to accidentally occur.

All of these predictions must be regarded as highly tentative. Even after the 100 years of research inaugurated by the Challenger Expedition, the amount of available data on the deep-sea community is very small, much too small to form a sufficient base for such an important conclusion. Much more needs to be learned about the structure and dynamics of this community before one can have confidence in predictions about cycling rates, transport vectors, and community sensitivity.

To date nothing is known about the ways in which deep-sea organisms will respond to exposure to radionuclides. We need to learn which substances are biologically active and to what extent. Which of these substances are lethal, and in what concentrations? What will be the pathways of their movement, and at what rates? Some of these questions have been partially answered for shallow-water organisms, but anything more than limited extrapolation is entirely unjustified.

Finally, any predictions based on these studies must be tested in a field simulation of a potential leakage before any degree of safety can be assured. A community is too complex to allow accurate prediction through simple addition of component processes. However, even a simulation must be treated with caution. In a study of the effect of chronic gamma radiation on an oak-pine forest, Armentano and Woodwell (1976) detected changes after twelve years that could not have been predicted after four. Thus, there is the likelihood that with the slowly paced deep-sea community a considerable amount of time would have to lapse before the effects of radionuclide leakage reached a stable condition.

The purpose of this article has been to discuss the potential consequences of high-level radioactive waste disposal in the deep sea. We have tried to avoid the question of whether it should or should not be done. Such a decision is ultimately a sociopolitical one. The scientist's role is to supply sufficient information to allow the decision to be intelligently made. Some of the issues will be quite subtle. For example, of what possible consequence could it be to eliminate a few deep-sea species of worms or clams? Could the risks outweigh the benefits of utilizing the deep-sea floor for any purpose whatsoever? Wilson and Willis (1975) have written a cogent rationale for prevention of extinction. Their arguments should be mandatory reading for anyone involved in decisions that might bear upon the question of species extinction. To underscore one of their points, extinction of the horseshoe crab might only a few years ago have been thought of as a loss to no one other than a few phylogenists, but that animal now occupies a key role in biomedical research of human disease mechanisms (Thomas, 1976). Obviously, the final decision of where to place radioactive wastes will not be an easy one, and, unfortunately, probably not a perfect one.

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Seabed Emplacement and Political Reality

by David A. Deese

No assessment of a sub-seabed option for the disposal of high-level radioactive wastes would be complete without an analysis of the parallel political, legal, and institutional implications of such a concept. These considerations could prove to be at least as complex as the scientific endeavors. The path to a sub-seabed option divides in several directions through a thicket of conflicting national and international interests. Which way the United States might ultimately decide to turn would be largely dictated by the extent to which the country decided it must rely on a sub-seabed option for future nuclear waste disposal.

Where do we stand at present on the national and international paths toward a sub-seabed option? We can say that the option is scientifically and technically plausible, but that it could turn out to be unworkable from a legal and political point of view. On the other hand, the national and international mechanisms exist that could, if judiciously set in motion, make it the most viable of all alternatives. To understand the complex international and national procedures that would be necessary to adopt this option, it is first necessary to briefly call to attention the recent efforts to dispose of high-level radioactive wastes.

For many years, the waste management component of nuclear energy programs in this country and elsewhere received very low priority treatment. However, the large increase in the United States waste management budget for 1976-1977 is evidence of a very recent transition to a high-interest program with considerable institutional and financial support (Figure 1).

One reason for this growing interest is that radioactive waste management has become one of the two or three major issues raised by opponents of nuclear energy. Many groups are now focusing on high-level waste disposal as the primary defect in increased reliance on this power source. Severe pressure to demonstrate waste disposal technologies has developed from environmental and political opposition to the construction and operation of more nuclear power plants, the reprocessing of spent fuels, and the over-all expansion of nuclear energy, including the risks of further proliferation of nuclear weapons.

Proposals to bury high-level radioactive wastes at land sites around the United States are now advancing rapidly. In December of 1976, the Energy Research and Development Administration (ERDA) announced that six waste repositories in salt beds,

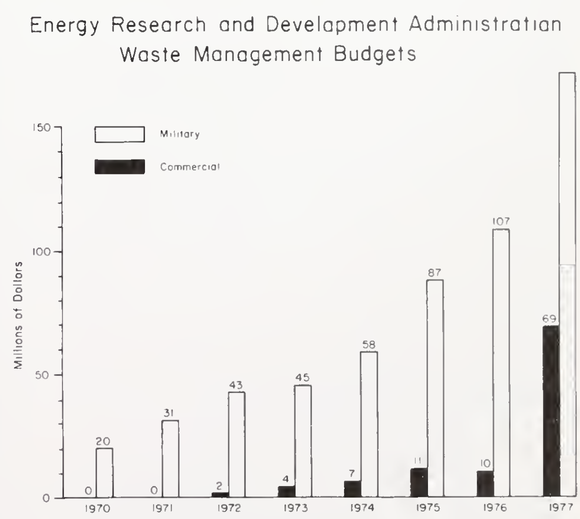


Figure 1. The Energy Research and Development Administration's commercial and military waste management budgets for 1970-1977 (the Atomic Energy Commission was split into ERDA and the Nuclear Regulatory Commission in 1974). (Source: ERDA.)

shale, or granite would be established by the year 2000. A decision on the first site is expected to be made by early 1979. Two similar repositories are apparently planned for the disposal of military wastes.

But the Federal government is continuing to encounter opposition from environmental groups, states, resource-based industries (with salt bed interests), and federal agencies. Kansas, for example, was successful recently in terminating an effort to use its salt beds for high-level waste disposal. On November 2, 1976, two counties in Michigan's upper peninsula separately rejected (by 2 to 1) Federal high-level waste repositories. This came after ERDA had given all states a strong assurance of full participation (interpreted by some as virtual veto power) in current siting considerations. Before licensing any new nuclear plants, California, early in 1977, started hearings and studies, under a 1976 law, to determine the adequacy of Federal waste management capabilities.

While ERDA officials are optimistic about finding acceptable sites that would offer new employment opportunities, technically and politically speaking it is nowhere near a certainty that acceptable sites can be found. This is particularly true as long as state and local officials have veto power over siting decisions. Additionally, the Nuclear Regulatory Commission (NRC) is still in the process of formulating goals on high-level waste disposal. An NRC Workshop in November of 1976 in Keystone, Colorado, concluded that potentially suitable sites exist in northern North America, Canada, and Western Australia (pre-Cambrian granite shield rocks), and the mid-plate region of ocean tectonic plates.

All the concerted pressure for a disposal solution on the part of environmentalists and others could have a negative effect on developing a sensible waste management program. The present race by ERDA to solve the disposal problem might curtail the essential careful investigation, testing, and evaluation of all serious options. It also could lead to inadequate demonstration of technologies before implementation, and to delays and errors that would further heighten public distrust. Thus, the NRC and the public should be brought into the decision-making process at a very early stage.

The United States is not alone in the disposal problem. There are considerable quantities of high-level wastes in China, the Soviet Union, France, and Britain. And small, but increasing, quantities are accumulating in countries with pilot reprocessing facilities. Table 1 provides an overview of the primary non-Communist reprocessing waste sources.

Every country operating nuclear reactors for energy has, or will soon have, highly radioactive spent fuel bundles in storage (Table 2). These must either be finally disposed of, creating a throwaway cycle, or reprocessed, creating a large variety of waste streams for further management (see page 4). Even if reprocessing were to be done externally, the country of origin might well have to take the wastes back (Figure 2).

All nations with major energy programs agree that it is necessary to solidify high-level wastes after an initial cooling period. But the technology required for the most effective solidification is not available to all nations. For example, France and the Soviet Union, both well advanced in this area, are reluctant to divulge the technologies.

Other countries are exploring alternate disposal concepts, but there are no common international criteria or standards to guide individual national efforts. And, as with the high-level waste solidification process, any effective technology that may be developed is likely to be kept secret.

Most nuclear countries are studying

Figure 2. Containers of radioactive wastes from Italian commercial reactors arriving in Britain in 1975 for reprocessing at the Windscale plant, Cumbria. (AP photo)

Table 1: Summary of world reprocessing projects, excluding Communist countries.

Location	Capacity t/y	Date operational	Status
Argentina	200 Kg/y	1968	Small hot cell. Shut down. Scheduled for reactivation in 1977.
Belgium			
Mol	60	1966	Shut down. Eurochemic has terminated reprocessing operations in its first plant. Has been used for reprocessing development. 167 tons of uranium processed.
Brazil		1981	Site selection in progress. Pilot plant.
Britain			
Windscale	1500-2500	1964	Operating near full capacity. Head end improvement program in hand.
	300	1972-73	Operated but shut down for investigation of incident and subsequent modification. Processed 100 t.
	400	1977-78	Will feed into natural uranium separation plant depending on availability of capacity.
	1000	1984	For expected domestic requirements part of United Reprocessor's plan.
	1000	1987	Awaiting decision on public acceptability of overseas contracts.
France			
La Hague	800	1966	Main plant for reprocessing EdF natural uranium fuel but due to be changed over to oxide.
	150-180	1976	Phased build up feeding into existing separation plant.
	1000	1985	Detailed design just starting.
Marcoule	900-1200	1958	Early military plant. Will take over commercial natural uranium from La Hague.
Germany			
Karlsruhe WAK	40	1970	Operating with fuel of increasing burnup. 32 tons of uranium processed.
—	1500	1984	Design specification being prepared. Site to be selected.
India			
Trombay	80	1965	Data unavailable.
Tarapur	150		Conducting test operations.
Israel	—	—	Data unavailable.
Italy			
Saluggia Eurex 1	10	1969	Currently shut down for modification.
Japan			
Tokai Mura	200	1976	Non-active commissioning. Full operation expected 1978.
—	1000	late 1980s	Projected if site can be found.
Spain			
Moncla	100 Kg/y		Data unavailable.
Taiwan	100s grams/y		Small pilot plant.
United States			
West Valley,	300	1966-72	630 t processed before shut down for expansion.
N.Y.	750	early 1980s	Dependent on new construction permit.
Morris, Ill.	300	—	Inoperable in present form. Currently providing fuel storage.
Barnwell, S.C.	1500	1977-78	Depending on Nuclear Regulatory Commission decisions.
—	—	mid-1980s	Looking for site.

Note: Several other pilot and laboratory scale plants have and are being operated for development of reprocessing technology. Commercial reprocessing of research reactor fuel has also been undertaken in several plants around the world. Fast reactor oxide fuel will be reprocessed in pilot scale plants in France and Britain and a plant for mixed thorium uranium oxides was built in Italy but has not been operated. Source: Adapted from *Nuclear Engineering International*, February 1976. Also: *Moving Toward Life in a Nuclear Armed Crowd?* Table A4, pp. 265-266, report for U.S. Arms Control and Disarmament Agency by Pan Heuristics, Los Angeles, Calif. 1976.

Table 2: World list of nuclear power plants (30 MWe and over).

Country	Units in commercial operation	Units under construction, on order, or letter of intent
Argentina	1	1
Austria	-	1
Belgium	3	4
Brazil	-	3
Bulgaria	2	2
Canada	6	14
Czechoslovakia	1	4
Finland	-	4
France	10	34
East Germany	3	4
West Germany	7	20
Hungary	-	4
India	3	5
Iran	-	4
Italy	4	5
Japan	12	13
Luxembourg	-	1
Mexico	-	2
The Netherlands	2	-
Pakistan	1	-
Philippines	-	2
Poland	-	1
Rumania	-	1
South Korea	-	3
Spain	3	11
Sweden	5	7
Switzerland	3	5
Taiwan	-	6
Britain	29 (10 under 100 MWe)	10
United States	56	155
Soviet Union	12	13
Yugoslavia	-	1

Note: Sizes of reactor units vary considerably. There also are significant quantities of wastes that have been generated from military programs in the United States, the Soviet Union, China, France, and Britain. Adapted from *Nuclear News,* August, 1976.

geologic formations as their prime option for final high-level waste disposal. At the moment, only West Germany has an operational repository for wastes at the Asse Salt Mine. However, this complex will only serve as a test facility for high-level wastes. Aside from the West German focus on salt and American plans to use salt and rock formations eventually, no countries have made commitments to specific land disposal sites for high-level wastes.

Some countries, such as Japan, Switzerland, Belgium, Britain, and The Netherlands, have serious geographic, demographic, geologic, or hydrologic restrictions. Most nations do not have the vast land areas that are available to the United States, the Soviet Union, and Canada. Added to these physical constraints is the growing environmental, consumer, and political opposition to nuclear energy. This opposition has highlighted two key factors: 1) the sensitivity of national groups to the prospect of offering territory that would be used as a repository for another nation's high-level wastes, and 2) the highly interdependent nature of decision-making in the international system.

Thus, some nuclear powers, such as Britain, may have to find disposal sites outside their borders, perhaps in countries without nuclear programs or in specially designated international areas (islands, seabed, etc.). All told it is possible that many countries without major nuclear energy programs will become directly involved through international organizations in the final disposal of high-level wastes.

Delays in the construction and licensing of facilities abroad, just as in the United States, are translated into higher energy costs and revised plant construction plans. The result has been increasing

interest among the highly industrialized countries in an acceptable high-level waste disposal solution. This has led to a significant, but very reticent, expansion of the International Atomic Energy Agency's (IAEA) program on waste management. (The IAEA, based in Vienna, is an autonomous agency of the United Nations that is charged with both promoting the peaceful uses of nuclear energy and preventing its application to military purposes among its 110 members.) However, disposal programs in the major nuclear nations are still in the very early stages of development, and serious efforts by the IAEA to solve this problem are just beginning.

Past Marine Disposal Practices

In 1970, the United States, continuing its routine disposal practice of the late 1960s, dumped 418 vaults of obsolete nerve gas rockets into the Atlantic. This was done despite a clamor that included congressional hearings, legal suits, and international protests. The UN Seabed Committee delivered an after the fact

> *. . . appeal to all governments to refrain from using the seabed and ocean floor as a dumping ground for toxic, radioactive, and other noxious material which might cause serious damage to the marine environment.*

In 1971, only rapid action by the U.S. Environmental Protection Agency (EPA) and a separate law suit prevented an American company from dumping 70 tons of arsenic compound into the Atlantic Ocean 50 miles from the East Coast. Also in that year, strong protests from Norway, Iceland, Ireland, and Britain, coupled with internal pressures from The Netherlands, led a Dutch chemical company to recall a tanker that was planning to dump 600 tons of a toxic chemical into the Norwegian Sea, or into the Atlantic Ocean as a back-up site.

By 1975, the Finnish government could rely on the spirit of international marine pollution conventions (that it had signed but not yet ratified) for the recall of an oil-company tanker. The ship was scheduled to dump arsenic poison into a remote area of the South Atlantic Ocean. The action was based on policy considerations rather than any legal obligation and was apparently taken without international pressure.

The public concern today over ocean dumping is also based on past and present sources of radiological contamination of the marine environment. Low-level wastes have been introduced into the oceans from the atmosphere (worldwide fallout from nuclear weapons); from ship discharges; from industrial discharges into rivers, tidal estuaries, and coastal waters (see *Oceanus,* Fall 1976, page 18); and from direct dumping.

Between 1946 and 1970, the U.S. Atomic Energy Commission (divided into ERDA and NRC in 1974) licensed the dumping of more than 86,000 containers of low-level wastes, totaling 94,000 curies, into the Atlantic (80,000) and Pacific (14,000) Oceans. After a protest by Mexico in 1959 over a license for a proposed dump into the Gulf of Mexico, the United States ended all licensing of commercial marine disposal operations and severely curtailed radioactive waste disposal into oceans. The practice was completely phased out in 1971 because of the prospect of acceptable land-based alternatives.

Britain dumped about 45,000 curies of low-level radioactive waste into the Atlantic from 1951 through 1966. Relatively shallow sites were used until the 1960s, when there were several shifts to progressively deeper water. Starting in 1967, Britain has conducted its dumping under the auspices of the Nuclear Energy Agency (NEA).

The NEA, which before 1972 was known as the European Nuclear Energy Agency, is a body associated with the Organization for Economic Cooperation and Development (OECD). It conducted dumping operations in 1967, 1968, 1969, and from 1971 to 1976 with solid wastes packaged in 55 gallon drums from varying combinations of eight European countries (Figure 3). They have

Figure 3. Radioactive wastes from a Belgian nuclear reactor plant being loaded aboard a Glasgow-based freighter prior to being dumped into the Bay of Biscay off the Spanish coast in 1971. (AP photo)

involved almost 300,000 curies of low-level and medium-level wastes. While three different sites in the northeast Atlantic have been used, the current one is about 1,000 kilometers from the European coasts (circle of 70 nautical miles diameter centered on 46°-15′N and 17°-25′W) and has an average depth of 4.5 kilometers.

The NEA dumping operations offer a good example of regional international cooperation, yet the extent of actual international oversight is minimal and the oceanographic model developed for hazard assessment is now acknowledged to be deficient. Though these operations do not approach the comprehensive arrangement that would be essential for any high-level waste disposal operation, they come closer than any of the various unilateral disposal operations conducted in the past.

International political responses to the NEA dumping operation have ranged from vocal support by the OECD, which holds that it is so safe that monitoring is not necessary, to outspoken opposition by the Russians, who consider it illegal pollution of the oceans. The Scandinavian countries recently have been careful to ensure that they are not associated with the NEA dumping program. Many others appear to be indifferent.

From a scientific point of view, it is very difficult to determine if damage has occurred or if a real hazard exists. While there has been no monitoring of these NEA sites, the results of an EPA study of low-level radioactive waste disposal sites in waters off the United States will be instructive. This work, currently in progress, should serve to refine our present policy of containment, provide specific regulations for ocean dumping of radioactive materials, and clarify U.S. policy toward the NEA dumping program.

There has been enough worldwide concern over the disposal of noxious substances in the oceans to produce two important philosophical shifts in the last five years: 1) a solid start toward considering the marine environment as one that should be protected in the same way as continental areas; 2) a distinct trend in thinking toward containment of toxic substances outside the biosphere rather than dilution and dispersal within it.

The U.S. Regulatory Posture

The United States, after many years of being a leading contributor to the pollution of the marine environment, has now taken a principal role in some fields involving its protection. This new interest began in 1970, when the Council on Environmental Quality forwarded a report to former President Nixon. This report served as the basis for national legislation and international proposals on the prevention of marine pollution by dumping. U.S. efforts in this regard were particularly intensive prior to the 1972 UN Conference on the Human Environment; one important result was the U.S. Marine Protection, Research, and Sanctuaries Act of October 23, 1972.

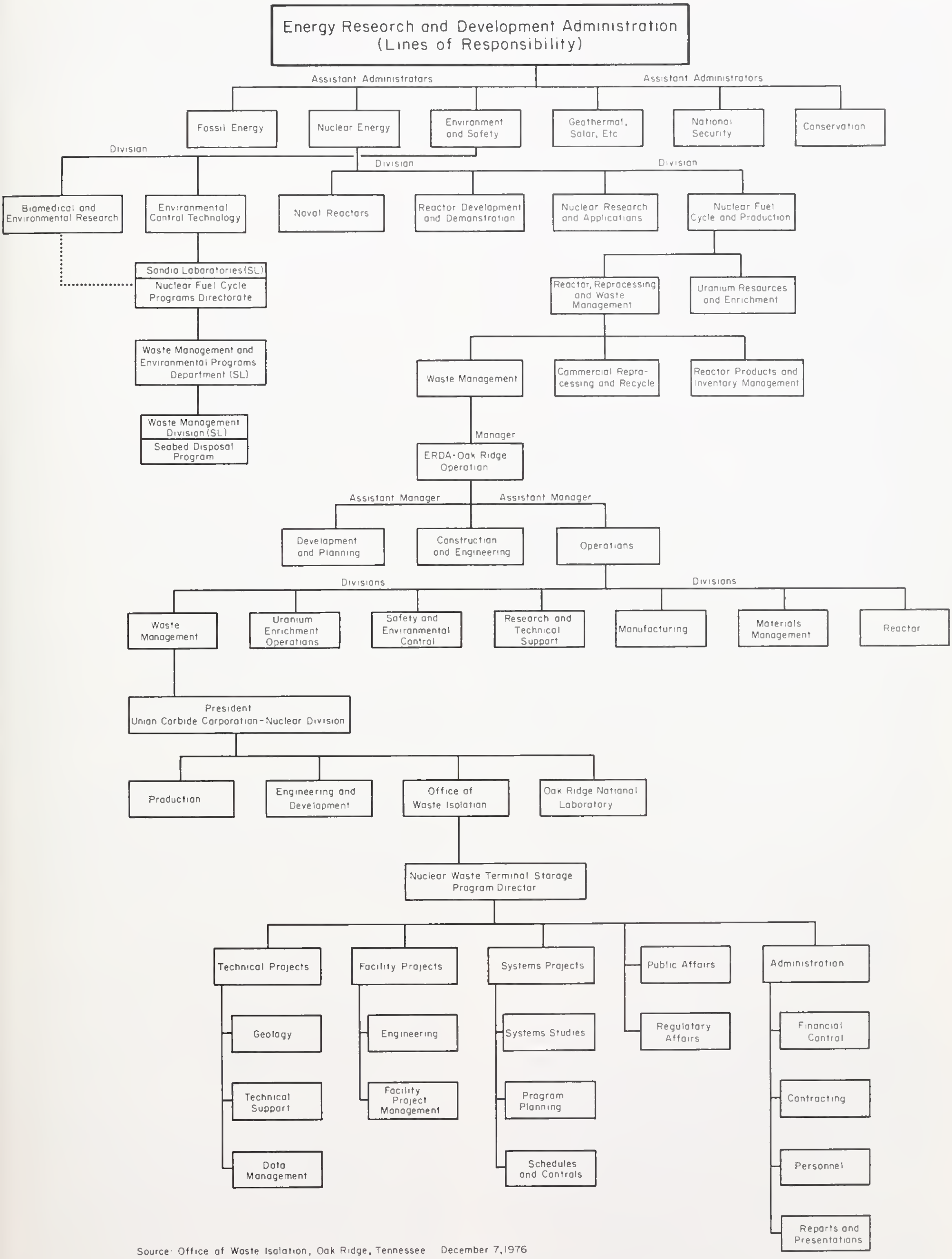
Since the definition of "dumping" included in this act probably covers sub-seabed disposal of high-level radioactive waste (the act bans the transport to sea for dumping of high-level waste — see page 6, *Oceanus*, Summer 1976), this disposal method would seem to be banned for all U.S. vessels, as well as for foreign vessels loaded in American ports. While the EPA has the authority under the act to issue permits for the dumping of low- and medium-level radioactive waste, it has no similar control over high-level wastes. Thus, Congress would have to amend the act, if the government decided to implement any form of sub-seabed disposal of high-level wastes.

It is not clear, however, whether an experimental high-level radioactive waste disposal project would constitute dumping if the wastes were emplaced in the deep seabed for testing in a retrievable condition. Such a pilot program would seem to be allowed by the act, which exempts from dumping "the intentional placement of any device . . . in the submerged land beneath such (ocean) waters, *for any purpose other than disposal,* when such . . . emplacement is otherwise regulated by Federal or state law or *occurs pursuant to an authorized Federal or state program*" (emphasis added). The question would center on how "scientific research," and "disposal" were defined, based on such factors as the extent to which retrievability could be shown and the intent of the program at the time the unit was established.

ERDA is responsible, under the National Environmental Policy Act of 1969, for the environmental assessment of planned high-level waste disposal techniques. It must, the act states, "utilize a systematic, interdisciplinary approach, which will insure the integrated use of the natural and social sciences."

Given the policy of the President's Council on Environmental Quality (that impacts abroad also must be considered), ERDA's assessments will likely include the international implications of U.S. participation in a sub-seabed program.

For domestic research and development programs, the timing of environmental impact statements must be "late enough in the development process to contain meaningful information, but early



The Energy Research and Development Administration structure for managing nuclear wastes.

enough so that this information can practically serve as an input in the decision-making process" (*Scientists' Institute v. AEC (1973) and Council on Environmental Quality Guidelines for Environmental Impact Statement Preparation*).

With respect to the dumping of radioactive wastes *into the sea,* the NRC presently has concurrent jurisdiction with the EPA based on a rule established by the old Atomic Energy Commission in 1971. The AEC stated that it would

> . . . *not approve any application for a license for disposal of licensed material at sea unless the applicant shows that sea disposal offers less harm to man or the environment than other practical alternative methods of disposal.*
> (10 Code of Federal Regulations, Sec. 20.302)

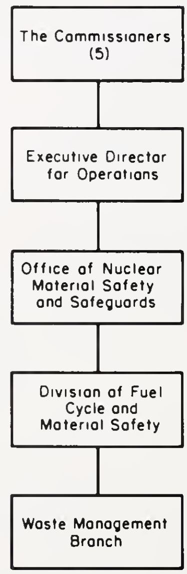
This was a significant shift of the burden of proof to the disposing party, though it is unclear as to whether "sea disposal" would apply to sub-seabed emplacement. If Congress were to amend the Marine Protection, Research, and Sanctuaries Act to allow sub-seabed disposal, permission for such disposal would probably then be required from the Nuclear Regulatory Commission and the Environmental Protection Agency.

The Code of Federal Regulations, incidentally, requires that high-level radioactive waste be disposed of in a Federal repository. But it is not so much how present regulations "read" as what they will "say" after the NRC updates them that will matter. This is especially true of the NRC's responsibility to license ERDA facilities for high-level waste disposal. According to recent testimony by NRC personnel before the Joint Committee on Atomic Energy:

> *New regulations will be structured to require conformance with a fixed set of minimum acceptable performance standards (technical, social, and environmental) for waste management activities, while providing for flexibility in technological approach* (Marcus A. Rowden, Chairman, NRC, May 12, 1976).

While specific criteria and standards for new regulations are still to be developed, recently established NRC goals include: 1) "isolation of radioactive wastes from man and his environment for sufficient periods to assure public health and safety, and preservation of environmental values"; and 2) "reduction, to as low as reasonably achievable, of a) the risk to public health both from chronic exposure associated with waste management operations and possible accidental releases of radioactive materials from waste storage, processing, handling or disposal"; and reduction of b) "long-term commitments (land-use withdrawal, resource commitment, surveillance requirements, proliferations, etc.)." Thus, the ultimate evaluation of the potential ERDA seabed disposal concept by the NRC will be made with a specific set of technical, social, and environmental standards in mind.

Nuclear Regulatory Commission



Primary lines of responsibility for radioactive waste management in the Nuclear Regulatory Commission. (Source: NRC)

The EPA interprets its role in this area to include the development of standards and criteria that will provide general guidance on environmental acceptability. In the case of seabed disposal, these standards and criteria would be employed by the NRC as an aid in evaluating the methodology, the sites selected, and operational aspects.

The EPA also has direct regulatory responsibility for issuing ocean disposal permits. So, if the Congress were to amend the Marine Protection, Research, and Sanctuaries Act of 1972 to allow ERDA to employ sub-seabed disposal of high-level wastes, the EPA would likely be given the permit-granting authority. Based on present work and trends within the EPA, the primary criterion for any decision on radioactive waste disposal in the marine environment, especially disposal of high-level radioactive waste, would probably be effective containment outside the biosphere. The EPA also would likely take a very serious look at any commitment of present or potential resources in the proposed disposal area.

The International Regulatory Situation

The definition of marine pollution that seems to have gained the widest international currency during the last five years includes:

> *The introduction by man, directly or indirectly, of substances or energy into the marine environment that results,* or is likely to result, *in such deleterious effects as harm to living resources, hazards to human health,* hindrance to marine activities *including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities* (*Emphasis added*). From the negotiating text of the Third UN Law of the Sea Conference.

Given that the containment system for radioactive wastes must conform to some acceptable level before sub-seabed disposal could become a viable option, the only way to label this as pollution might be as a "hindrance to marine activities." Yet effects on foreseeable potential uses of the seabed or oceans would appear to be minimal. The only essential ban would be on activities involving penetration of small areas of the seabed where wastes have been emplaced.

If we assume that seabed disposal of radioactive wastes would constitute pollution of the marine environment in some sense or other, it is important to determine what category of pollution would apply for purposes of regulation and control, or prevention. The negotiating text of the UN Law of the Sea Conference mentions three potentially relevant categories:

1. "Pollution from installations and devices used in the exploration and exploitation of the natural resources of the seabed and subsoil." This comes close to applying to sub-seabed disposal, but use of the area for high-level waste disposal would not, without some strain in interpretation, fall under resource exploitation.

2. "Pollution from all other installations and devices operating in the marine environment." This may be the closest to describing seabed disposal. It is a catch-all to cover sources besides pollution from the continents, the atmosphere, vessels, dumping, and seabed exploitation.

3. "Release of toxic, harmful and noxious substances, especially those which are persistent, by dumping." This reintroduces the topic of the international dumping regime. Throughout 1971 and 1972 and particularly in preparation for the UN Conference on the Human Environment there was a strong push for an international agreement on ocean dumping. The outcome: the Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter in the Oceans (London Convention) of December 29, 1972. With 15 ratifications, it entered into force on August 30, 1975, and, by September 1976, twenty-nine countries had ratified or acceded to the Convention, including the United States, the Soviet Union, Britain, Canada, Mexico, Norway, Panama, and Spain.

Though the "release of toxic . . . substances" would not apply to an acceptable containment system within the seabed, dumping may apply, depending on how nations interpret the London Convention. The Convention defined dumping as "any deliberate disposal *at sea* of wastes . . . from vessels . . . at sea" (emphasis added). There are at least two possible interpretations of the wording "at sea" in this context: 1) that it refers to the location of the disposing party, i.e., any disposal from vessels that are at sea constitutes dumping, regardless of whether there is any possibility of the wastes eventually reaching the water (thus, sub-seabed disposal would be dumping); and 2) that any disposal from vessels resulting in the discharge of wastes, whether containerized or not, into the water and/or onto the seabed constitutes dumping (sub-seabed disposal would not be dumping).

The London Convention assigned to the IAEA the task of defining high-level radioactive wastes that are unsuitable for dumping at sea. The first draft of the IAEA definition, since superseded, included the following comment on the sub-seabed disposal of wastes:

> *Certain methods of radioactive waste disposal, although not feasible at this time, may eventually be developed technically to the point of proposing the long-term isolation of wastes by emplacement beneath the seabed. Such methods should be evaluated as variations of deep geological burial on land and are excluded from the scope of this document because they will not contribute to the radioactivity of the sea* (GOV/1622, Appendix, p. 7, Sept. 3, 1973).

A series of three advisory group meetings, running from December 1976 to July 1977, will develop a more acceptable definition based on a revised oceanographic model. Present intentions are to have a fully accepted definition of high-level waste unsuitable for dumping for submission to the IAEA Board of Governors and the parties to the London Convention in 1978.

Another indication of how the London Convention definition on dumping will be interpreted can be drawn from the national dumping legislation that has been passed by countries which have ratified the London Convention. The Canadian

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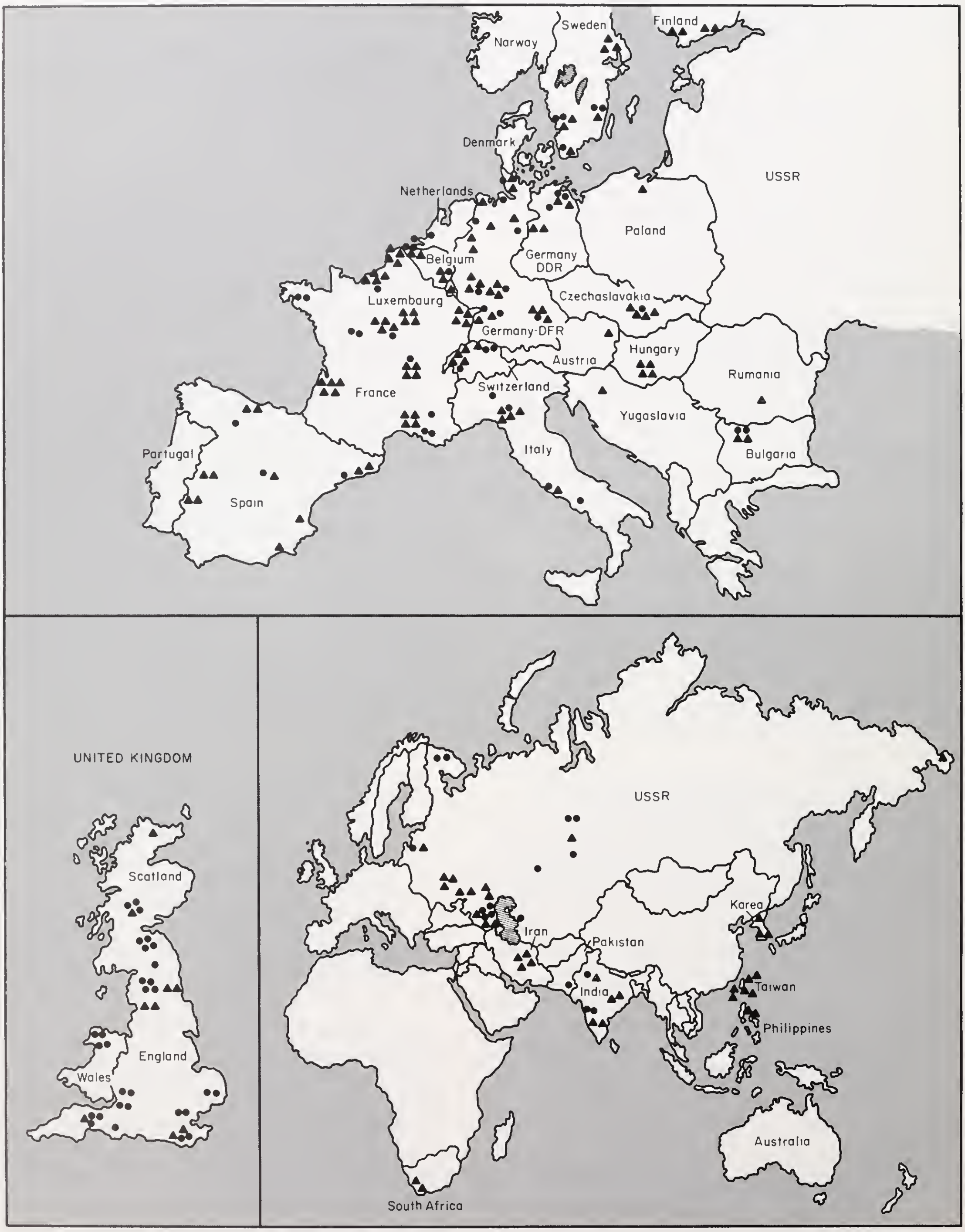
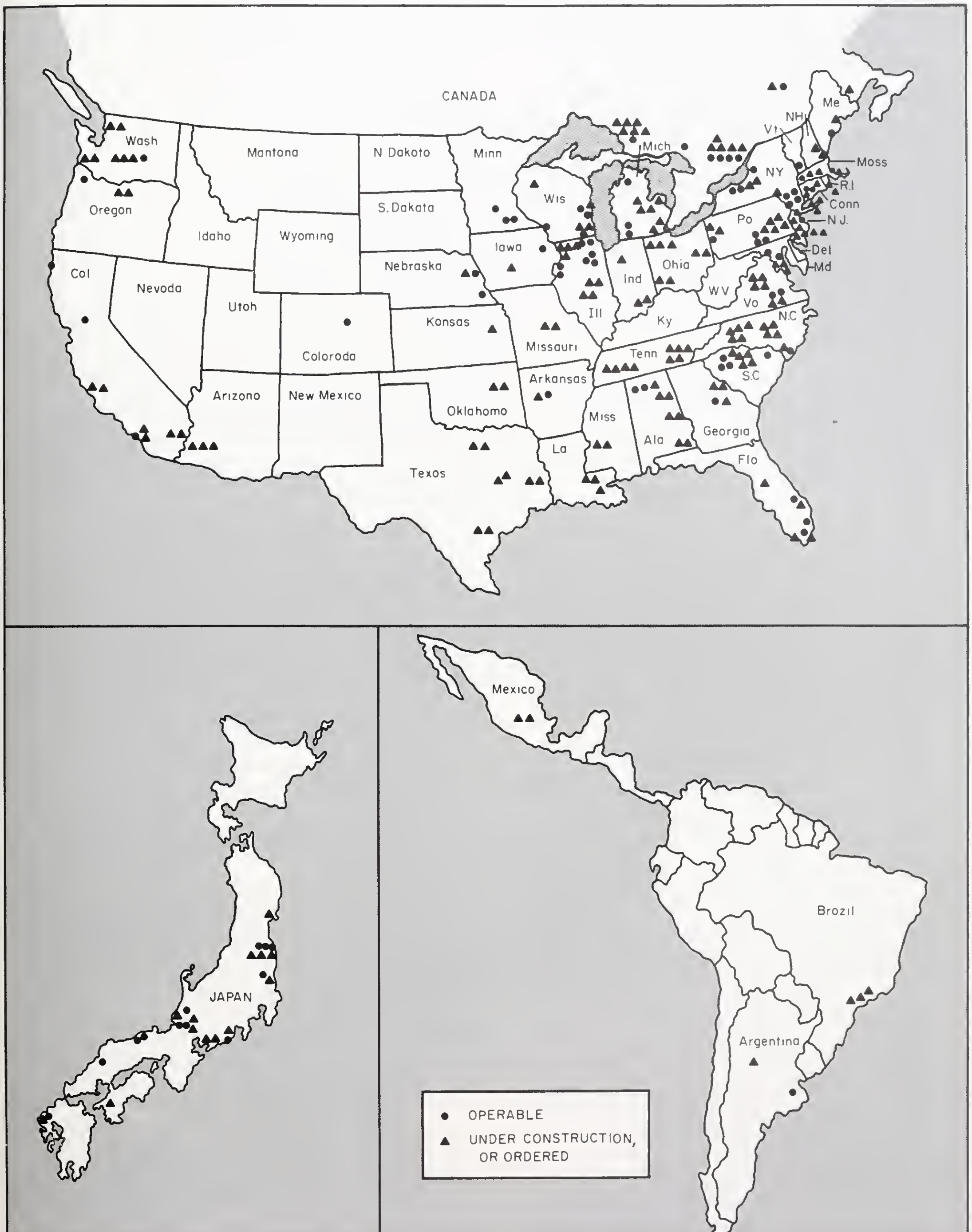


OPERABLE, UNDER CONSTRUCTION, OR ORDERED



Adapted from data supplied by *Nuclear News*, September 1976, and from U S ERDA

definition — "any deliberate disposal from ships . . . at sea of any substance" — would certainly include the seabed disposal of wastes. The wording of the British definition — "permanently deposited in the sea" — would clearly exclude seabed disposal. Earlier legislation from Finland, Norway, Sweden, and Denmark would not define seabed disposal as dumping because of the use of the phrase "disposal into, or in, the high seas." Finally, the European Economic Community (EEC) seems to be moving toward a definition that would exclude seabed disposal. They would consider "any deliberate disposal of substances and materials into the sea . . ." as constituting dumping.

International Seabed Guidelines

There are some guiding principles for use of the deep seabed that should help us in judging the international acceptability of nuclear waste disposal in this area. There is wide agreement among nearly all countries in the UN that the seabed beyond the limits of national jurisdiction (or "Area"): 1) should be managed internationally; 2) must be used in accordance with international law and the UN charter; 3) must be reserved for peaceful purposes; and 4) is the common heritage of mankind. These principles have been derived from the work of the UN General Assembly and have been reinforced during the Third UN Law of the Sea Conference.

International management has so far been narrowly defined in Law of the Sea (LOS) negotiations due to an obsession with the issue of potential mining of manganese nodules. Though this part of the LOS negotiating text is unsettled, it appears certain that any International Seabed Authority would have jurisdiction only over activities in the seabed beyond national limits. Furthermore, the definition of activities would be limited to exploration and exploitation of resources, with the latter defined as constituting only in situ minerals.

While waste disposal does not fall under exploiting minerals, there are three avenues by which an International Seabed Authority might acquire some role in a potential sub-seabed program:

1. The general coverage of scientific research in the Area. A sub-seabed program would involve detailed work at each site for several years and some form of monitoring for longer periods. There is nothing in the very general coverage of the LOS negotiating text to date that would restrict this type of research.

2. The need to protect the marine environment. The treaty to date offers only very specific coverage of harmful effects from "activities in the Area." It appears that the International Seabed Authority will not receive, at least initially, a strong and comprehensive mandate to protect this section of the marine environment.

3. An obligation to accommodate other activities in the marine environment with mining activities. Though the Authority will probably not be given jurisdiction here, this obligation means that use of any parts of the Area for sub-seabed disposal cannot unreasonably restrict other uses, including resource development.

As referred to at the beginning of this section, the second guiding principle — use of the seabed in accordance with international law and the UN charter — is even less developed than that of international management. There is, however, a significant body of developing international law, including increasing evidence of a relatively high-level commitment to protect the marine environment. The basis of this developing law, largely contained in the results to date of the LOS conference, is the recent and reticent recognition by many states that

> *a growing class of environmental problems, because they are regional or global in extent or because they affect the common international realm, will require extensive cooperation among nations and action by international organizations in the common interest* (Report of the UN Conference on the Human Environment, 1972).

The ultimate disposal of high-level radioactive waste is clearly within this class of problems both because it is global in extent and because it could very well affect the "common interest" in various ways.

For all nations, the general obligations of marine environmental law as set forth in the LOS negotiating text are:

1. To protect and preserve the marine environment.
2. To take all necessary measures to ensure that pollution from incidents or activities under their jurisdiction or control does not spread beyond areas of national sovereignty.
3. To take all necessary measures to prevent, reduce, and control marine pollution from any source.

All nations may eventually be obliged to conform to the specific requirements of developing international environmental law (Table 3). These requirements also would become immediate obligations for all states signing and ratifying any future Law of the Sea treaty.

Table 3: Developing requirements of international environmental law*

1. Bilateral, regional, and broad international cooperation is to be conducted for studying all aspects of marine pollution and establishing scientific criteria for national and international standards and practices to protect the marine environment.

2. *Environmental assessments must be done by countries conducting activities that can reasonably be expected to cause substantial pollution of, or significant and harmful changes to, the marine environment.*

3. Environmental assessments and other reports on the risks and effects of marine pollution must periodically be published or distributed through international organizations; *prior exchange of information and consultation with potentially affected countries and organizations should take place in cases of potential damage to common international areas.*

4. Countries are responsible for their international obligations to protect the marine environment and liable for damage attributable to them from violations; they must cooperate in developing the international law of liability and damage assessment.

5. No international system of enforcement for environmental rules and standards over dumping or use of the deep seabed, beyond "activities in the Area," is envisioned; so individual countries, including flag, port and coastal countries, are to conduct most or all enforcement.

6. Countries must, as far as practicable, individually or collectively monitor the risks and effects of marine pollution; this is specifically to include *surveillance of activities permitted or conducted to determine whether they are likely to pollute the marine environment.* (Emphasis added)

*The UN Conference on the Human Environment (1972) and the ongoing Third UN Conference on the Law of the Sea.

The third guiding principle — that use of the Area should be reserved for "peaceful purposes" — remains undeveloped because of disagreement over interpretation. Certain countries would probably object to the disposing of high-level military wastes from weapons programs. However, there are pervasive health, safety, and nonproliferation reasons for treating all high-level waste as a unit.

The final principle — that the Area is the common heritage of mankind — is the least defined of all. Although it has never been formally accepted by the United States, there is agreement that this principle entails sharing potential mineral resources, furthering an international communal interest, and banning any national appropriation of the Area.

One possible legal and social implication of a sub-seabed program might be its effect on the "common international realm," which was mentioned in the preamble to the Stockholm Conference in 1972 with reference to the growing number of regional and global environmental problems. If a section of the Area were to be closed for resource exploitation, this might constitute national appropriation. It might then follow that specific consent from the international community, presumably represented by the International Seabed Authority, would be required because

> *no individual member of the community can assert a claim or right to enjoy the benefits of this "resource" except pursuant to arrangements which that community has sanctioned.* (J. L. Hargrove, in *Who Protects the Oceans?* 1975).

This goes considerably beyond the point to which the "common heritage" principle has been developed. So far, the applicable international arrangements consist of developing international standards to protect the Area from environmental damage, and a general commitment to its safe development and rational management.

A Look Into the Future

While adequate structures for implementation of an international sub-seabed program are lacking, there are useful regulatory and supervisory mechanisms that could help provide guidance. The task at hand is to investigate the ways in which these existing mechanisms, or new ones, can be developed on a parallel basis with science and technology. One means of such structuring is to consider the feasible scenarios, or management models, under which a sub-seabed disposal program might be conducted. A useful matrix can be established by lining up the key characteristics of any such program with the likely actors (Table 4).

Table 4

Key characteristics	*Likely actors*
Source of financing.	Corporation(s), private or private/public.
Technical framework.	
Source of standards and regulations.	Government(s), individually or loosely associated.
Responsible and liable parties.	Group(s) of governments; probable involvement of regional organizations; possible international agency participation.
Institutional structures.	
Source of enforcement and supervision.	Large number of governments; direct regional organization participation; significant role for international agencies.

Four management models result (Table 5). The first (Model 1) involves the possibility that some form of sub-seabed disposal would be organized, operated, and regulated along corporate lines (with public as well as private management in most countries). The second (Model 2) is heavily governmental in nature, with some influence from internationally established standards and regulations. Next (Model 3) is a regional plan with joint financing, development, and regulation coordinated by an international body. Finally, there is an international structure (Model 4) that would make use of political and geographic international regions to coordinate joint development, regulation, and control of a sub-seabed disposal program.

The four models are complementary. It is quite conceivable, for example, that some form of corporate participation could be included in Models 2, 3, or 4. Moving from Model 1 toward the greater levels of international participation in Models 2, 3, and 4 should increase the probability of effective regulation and enforcement. It is impossible, however, to rule out a responsible unilateral action.

The evidence strongly suggests that a sub-seabed program could be prevented or delayed by several national or international enforcement tools. All of our earlier examples of marine disposal practice show the growing trend toward unilateral and international action to prevent the disposal of hazardous wastes in the oceans. This took place under pressure from national, regional, and international sources through various mechanisms.

In addition to the international dumping regime, a widely accepted Law of the Sea treaty could also prevent the use of sub-seabed disposal, especially in the form of Models 1 or 2. This might be accomplished through a ban on national appropriation of deep seabed areas or by interpreting the definition of pollution in such a way as to forbid sub-seabed disposal.

Table 5

MODEL 1
Corporate

Largely corporate characteristics with significant governmental regulation if exclusively a private corporation.

MODEL 2
Governmental

Characteristics dominated by individual national governments; minimal direct regional/international influence.

MODEL 3
Regional

Joint financing, development, and regulation coordinated by regional (international) organization(s); regulatory and institutional aspects influenced directly by international agencies.

MODEL 4
International

Use of political and geographic international regions to coordinate broad international development, regulation, and control of sub-seabed disposal program; strong possibility of incorporation into broader international waste management or nonproliferation structure.

On the other hand, it seems that a sub-seabed program under Model 3 or 4 could be effectively supervised. Unprecedented levels of

international cooperation in the specific area of radioactive waste disposal would be essential to implement such an effort. The basic expertise and structures for supervising such a cooperative program, however, either exist or are well within reach.

While the main problem would be reaching agreement among participating nations on essential provisions, a significant portion of a draft treaty could be derived from work done in the late 1950s and early 1960s on low-level radioactive waste disposal. These efforts led to very strong recommendations for regulating and controlling low-level waste disposal *into the oceans*. They included provisions for national and international registration of all disposals, prior notification and consultation with affected nations and appropriate international bodies, and national and international licensing of disposal practices and sites. The recommendations also would sanction the IAEA to investigate and object to intended practices; assist nations with negotiations, site evaluation, and regulation and monitoring; monitor disposal operations and sites; and initiate certain penalties or sanctions. Close coordination with the UN Environment Program (UNEP) in this area would be crucial. UNEP was established in 1973 under the UN General Assembly to coordinate and oversee the environmental programs of all UN and associated bodies.

This is the basic framework, minus some system of strict liability and financial guarantees and/or incentives and a joint commission at the regional or international agency level, that would be required to ensure the type of regulation and control envisioned in Model 4.

International Political Acceptability

The most vital factor in gaining international political acceptability may be in developing public comprehension of the difference between the future concept of a sub-seabed program, and the past and present disposal into the oceans. If the sub-seabed program is seen as another category of the geologic disposal option, it could eventually prove to be more acceptable than any other solution.

Of the utmost importance to the political acceptance of a sub-seabed program is the extent to which it becomes an international effort. If there are a number of nations and some international agencies involved at the research and development (R&D) or pilot unit stage, the chances are greatly enhanced for building at least national and international acquiescence for this use of the seabed.

The largest international effort to date in this respect was the First International Workshop on the Seabed Disposal of High-Level Radioactive Wastes. It was sponsored by the NEA and ERDA at Woods Hole, Massachusetts, in February of 1976. It turned out, as intended, to be a scientific and technical effort to map a potential international program for the investigation and assessment of seabed disposal. There were representatives at the workshop from Australia, Canada, France, West Germany, Japan, the United States, Britain, the European Economic Community Commission, and the IAEA. France, Japan, and Britain have since indicated an interest in participating with the United States in a joint R&D effort. A Second International Workshop may be held later this year. The establishment of a multilateral R&D program through the International Energy Agency (IEA) and Nuclear Energy Agency would be the most highly developed international cooperative effort to date on radioactive waste management.

Also important to the political acceptability of a sub-seabed program is the international organization through which it is conducted (Figure 4). Both the IEA and the NEA are regional groups of highly industrialized nations, bearing the stigma of definitive political associations. Therefore, any international sub-seabed program might best be developed outside the existing IEA/NEA framework.

Key to the final adoption of such a program is the extent to which common ground can be developed between waste management and attempts to prevent the proliferation of nuclear weapons. (The management of spent fuel is affected by nonproliferation objectives and waste management may provide incentives for participation in nonproliferation arrangements.) The close interrelationship between these two areas of activity means that decisions made on nonproliferation matters could be vitally important to the acceptability of a sub-seabed program. If part or parts of the nuclear fuel cycle are internationalized, there could very well be at least one international waste disposal site.

If the United States or other nuclear powers harbor sites for international reprocessing facilities, there is a strong chance that some form of international waste disposal arrangement will be required. If reprocessing is either delayed or eliminated, there still will be strong incentive to establish an international spent fuel storage facility. This would then require some provision for conversion to a disposal site or other offsite arrangements for final waste disposal.

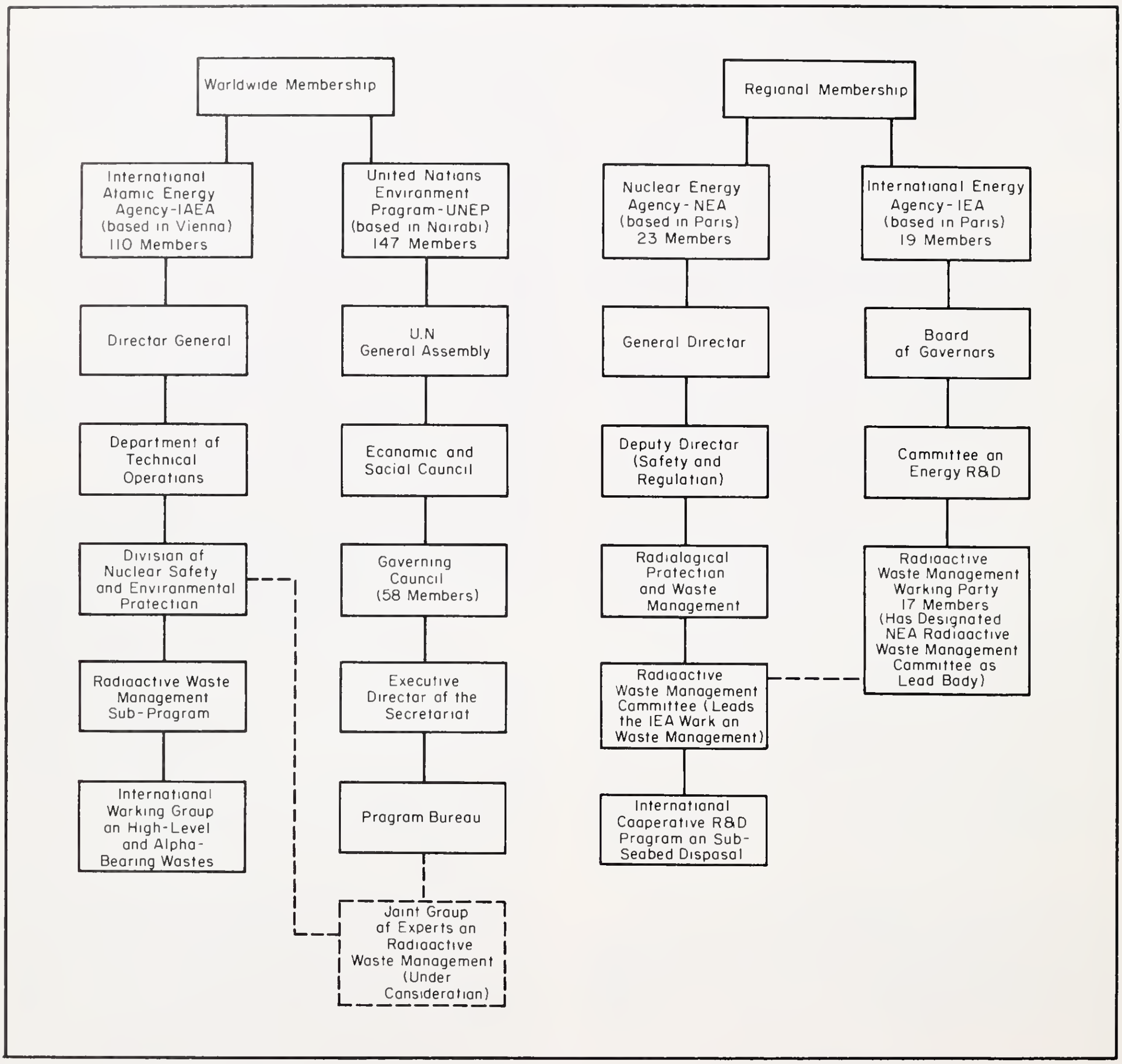


Figure 4. International agencies that would play major roles in managing an international program on the sub-seabed disposal of high-level radioactive waste. Only the most directly involved departments, divisions, and committees of each agency are included.

Conclusion

The outcome, of course, will be determined largely by the national political stances taken toward a sub-seabed disposal program. Political and diplomatic responses from individual countries should be expected to be heavily influenced by the number, type, and timing of options available for high-level waste disposal.

The budgetary and institutional support Washington gives to the sub-seabed program will have a crucial influence on the progress of sub-seabed science and technology over the next three to five years. Despite the growing need of nations, such as Japan and Britain, for a high-level waste disposal option, a sub-seabed program will probably not be employed if it is not strongly funded and supported by the United States.

Clearly, there are enough legal and political obstacles to destroy or delay a sub-seabed disposal program. The nontechnical hurdles to seabed disposal equal the scientific and technical ones. But, on the other hand, there are important potential social and political benefits to be gained from any serious attempt to mount a successful sub-seabed program. These lie principally in international

U.S. Waste Management Program Schedule

1977

- ERDA will issue a draft generic environmental impact statement on the management of commercial radioactive wastes for public review and comments.
- EPA will determine general performance criteria for establishment of new low-level waste land burial sites.
- NRC will publish an environmental impact statement for revised waste management regulation.*
- ERDA will publish a final environmental impact statement on reprocessing and announce a decision thereon.
- NRC will announce its decision on plutonium recycle.
- ERDA will publish a final generic environmental impact statement on management of commercial radioactive wastes.

1978

- NRC will publish final regulations for waste form and packaging criteria.
- ERDA will announce a decision on waste forms, storage modes, and packaging criteria to be used as basis for designing terminal storage facility.
- EPA will establish general environmental standards applicable to high-level waste management.
- ERDA will select site(s) for the underground excavation phase of the radioactive waste geologic program. (This action will be subject to the appropriate site-specific environmental impact statement.)
- NRC will establish criteria for long-term care for new low-level waste burial sites.

1979

- NRC will establish site selection criteria for new low-level burial grounds.

1985

- ERDA will start receiving solidified waste in pilot plant operations in a geologic terminal storage facility.

*The dates shown for major regulatory actions are estimates provided by the NRC. The NRC, an independent regulatory agency, points out that these dates cannot be predicted with certainty. Based on experience with regulatory process lead time, however, the time allowed in the program should prove sufficient to allow for full decision-making processes, including public participation.

Source: Federal Energy Resources Council

cooperation on waste management, environmental protection, nonproliferation of nuclear weapons, and governing the deep seabed.

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Glossary

actinides

A series of elements in the periodic table, beginning with actinium, element No. 89, and continuing through lawrencium, element No. 103. The series includes uranium, element No. 92, and all the man-made transuranium elements. All are radioactive.

alpha particle

A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together. It is the least penetrating of the three common types of radiation (alpha, beta, gamma) emitted by radioactive material, being stopped by a sheet of paper. It is not dangerous to plants, animals, or man, unless the alpha-emitting substance has entered the body.

atomic weight

The mass of an atom relative to other atoms. The present-day basis of the scale of atomic weights is carbon; the commonest isotope of this element has arbitrarily been assigned an atomic weight of 12. The unit of the scale is $^{1}/_{12}$ the weight of the carbon 12 atom, or roughly the mass of one proton or one neutron. The atomic weight of any element is approximately equal to the total number of protons and neutrons in its nucleus.

background radiation

The radiation in man's natural environment, including cosmic rays and radiation from the naturally radioactive elements, both outside and inside the bodies of men and animals. It is also called natural radiation.

beta particle

An elementary particle emitted from a nucleus during radioactive decay, with a single electrical charge and a mass equal to $^{1}/_{1837}$ that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron. Beta radiation may cause skin burns, and beta-emitters are harmful if they enter the body. Beta particles are easily stopped by a thin sheet of metal, however.

bone seeker

A radioisotope that tends to accumulate in the bones when it is introduced into the body. An example is strontium 90, which behaves chemically like calcium.

breeder reactor

A reactor that produces fissionable fuel as well as consuming it, especially one that creates more than it consumes. The new fissionable material is created by capture in fertile materials of neutrons from fission. The process by which this occurs is known as breeding.

capture

A process in which an atomic or nuclear system acquires an additional particle; for example, the capture of electrons by positive ions, or capture of electrons or neutrons by nuclei.

chain reaction

A reaction that stimulates its own repetition. In a fission chain reaction a fissionable nucleus absorbs a neutron and fissions, releasing additional neutrons. These in turn can be absorbed by other fissionable nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the number of neutrons released in a given time equals or exceeds the number of neutrons lost by absorption in non-fissioning material or by escape from the system.

cladding

The outer jacket of nuclear fuel elements. It prevents corrosion of the fuel and the release of fission products into the coolant. Aluminum or its alloys, stainless steel and zirconium alloys are common cladding materials.

control rod

A rod, plate, or tube containing a material that readily absorbs neutrons (hafnium, boron, etc.), used to control the power of a nuclear reactor. By absorbing neutrons, a control rod prevents the neutrons from causing further fission.

core

The central portion of a nuclear reactor containing the fuel elements.

curie

The basic unit to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion disintegrations per second, which is approximately the rate of decay of 1 gram of radium. A curie is also a quantity of any nuclide having 1 curie of radioactivity. Named for Marie and Pierre Curie, who discovered radium in 1898.

decay, radioactive

The spontaneous transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide. The process results in a decrease, with time, of the number of the original radioactive atoms in a sample. It involves the emission from the nucleus of alpha particles, beta particles (or electrons), or gamma rays; or the nuclear capture or ejection of orbital electrons; or fission. Also called radioactive disintegration.

disposal

Isolating the radioactive waste permanently in a form and manner that precludes retrieval.

element

One of the 103 known chemical substances that cannot be divided into simpler substances by chemical means. A substance whose atoms all have the same atomic number. Examples: hydrogen, lead, uranium. (Not to be confused with fuel element.)

excited state

The state of a molecule, atom, electron or nucleus when it possesses more than its normal energy. Excess nuclear energy is often released as a gamma ray. Excess molecular energy may appear as fluorescence or heat.

fission

The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but usually is caused by nuclear absorption of gamma rays, neutrons or other particles.

fission fragments

The two nuclei that are formed by the fission of a nucleus. Also referred to as primary fission products. They are of medium atomic weight, and are radioactive.

fission products

The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclides formed by the fission fragments' radioactive decay.

fuel

Fissionable material used or usable to produce energy in a reactor. Also applied to a mixture, such as natural uranium, in which only part of the atoms are readily fissionable, if the mixture can be made to sustain a chain reaction.

fuel cycle

The series of steps involved in supplying fuel for nuclear power reactors. It includes mining, refining, the original fabrication of fuel elements, their use in a reactor, chemical processing to recover the fissionable material remaining in the spent fuel, re-enrichment of the fuel material, and refabrication into new fuel elements.

fuel element

A rod, tube, plate, or other mechanical shape or form into which nuclear fuel is fabricated for use in a reactor. (Not to be confused with element.)

fuel reprocessing

The processing of reactor fuel to recover the unused fissionable material.

gamma rays

High-energy, short-wavelength electromagnetic radiation. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best stopped or shielded against by dense materials, such as lead or depleted uranium.

half-life

The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Measured half-lives vary from millionths of a second to billions of years.

half-life, effective

The time required for a radionuclide contained in a biological system, such as a man or an animal, to reduce its activity by half as a combined result of radioactive decay and biological elimination.

ion

An atom or molecule that has lost or gained one or more electrons. By this ionization it becomes electrically charged. Examples: an alpha particle, which is a helium atom minus two electrons; a proton, which is a hydrogen atom minus its electron.

ion exchange

A chemical process involving the reversible interchange of various ions between a solution and a solid material, usually a plastic or a resin. It is used to separate and purify chemicals, such as fission products in solutions.

isotope

One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights. An equivalent statement is that the nuclei of isotopes have the same number of protons but different numbers of neutrons. Thus, ${}^{12}_{6}C$, ${}^{13}_{6}C$, and ${}^{14}_{6}C$ are isotopes of the element carbon, the subscripts denoting their common atomic numbers, the superscripts denoting the differing mass numbers, or approximate atomic weights. Isotopes usually have very nearly the same chemical properties, but somewhat different physical properties.

natural uranium

Uranium as found in nature, containing 0.7% of ${}^{235}U$, 99.3% of ${}^{238}U$, and a trace of ${}^{234}U$. It is also called normal uranium.

neutron

An uncharged elementary particle with a mass slightly greater than that of the proton, and found in the nucleus of every atom heavier than hydrogen. A free neutron is unstable and decays with a half-life of about 13 minutes into an electron, proton, and neutrino. Neutrons sustain the fission chain reaction in a nuclear reactor.

nucleus

The positively charged center of an atom.

nuclide

A general term applicable to all atomic forms of the elements. The term is often erroneously used as a synonym for "isotope," which properly has a more limited definition. Whereas isotopes are the various forms of a single element (hence are a family of nuclides) and all have the same atomic number and number of protons, nuclides comprise all the isotopic forms of all the elements. Nuclides are distinguished by their atomic number, atomic mass, and energy state.

plutonium

A heavy, radioactive, man-made, metallic element with atomic number 94. Its most important isotope is fissionable plutonium 239, produced by neutron irradiation of uranium 238. It is used for reactor fuel and in weapons.

radiation

The emission and propagation of energy through matter or space by means of electromagnetic disturbances which display both wave-like and particle-like behavior; in this context the "particles" are known as photons. Also, the energy so propagated. The term has been extended to include streams of fast-moving particles (alpha and beta particles, free neutrons, cosmic radiation, etc.) Nuclear radiation is that emitted from atomic nuclei in various nuclear reactions, including alpha, beta and gamma radiation and neutrons.

radioactivity

The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation.

radioisotope

A radioactive isotope. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. More than 1300 natural and artificial radioisotopes have been identified.

radionuclide

A radioactive nuclide.

salt cake

The solid residue resulting from a concentration of high-level liquid waste in underground waste storage tanks.

thorium

A naturally radioactive element with atomic number 90 and, as found in nature, an atomic weight of approximately 232. The fertile thorium 232 isotope is abundant and can be transmuted to fissionable uranium 233 by neutron irradiation.

transmutation

The transformation of one element into another by a nuclear reaction or series of reactions. Example: the transmutation of uranium 238 into plutonium 239 by absorption of a neutron.

transuranic element (isotope)

An element above uranium — that is with an atomic number greater than 92. All 14 transuranic elements are produced artificially and are radioactive. They are neptunium, plutonium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, lawrencium, kurchatovium, hahnium, and 106 (recently discovered but not yet named).

uranium

A radioactive element with the atomic number 92 and, as found in natural ores, an average atomic weight of approximately 238. The two principal natural isotopes are uranium 235 (0.7% of natural uranium), which is fissionable, and uranium 238 (99.3% of natural uranium), which is fertile. Natural uranium also includes a minute amount of uranium 234. Uranium is the basic raw material of nuclear energy.

waste, radioactive

Equipment and materials (from nuclear operations) which are radioactive and for which there is no further use. Wastes are generally classified as high-level (having radioactivity concentrations of hundreds to thousands of curies per gallon or cubic foot), low-level (in the range of 1 microcurie per gallon or cubic foot), or intermediate (between these extremes).

Acronyms

AEC (U.S.) Atomic Energy Commission (divided into ERDA and NRC in 1974)
EEC European Economic Community
EPA (U.S.) Environmental Protection Agency
ERDA (U.S.) Energy Research and Development Administration
IAEA International Atomic Energy Agency (associated with United Nations)
IEA International Energy Agency
LOS Law of the Sea (ongoing negotiations at UN; first conference 1931, second 1958, third and current 1973)
LWR Light-Water Reactor
NEA Nuclear Energy Agency (formerly European Nuclear Energy Agency)
NOAA (U.S.) National Oceanic and Atmospheric Administration
NRC (U.S.) Nuclear Regulatory Commission
OECD Organization for Economic Cooperation and Development
R&D Research and Development
UNEP United Nations Environment Program

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Acronyms

AEC (U.S.) Atomic Energy Commission (divided into ERDA and NRC in 1974)
EEC European Economic Community
EPA (U.S.) Environmental Protection Agency
ERDA (U.S.) Energy Research and Development Administration
IAEA International Atomic Energy Agency (associated with United Nations)
IEA International Energy Agency
LOS Law of the Sea (ongoing negotiations at UN; first conference 1931, second 1958, third and current 1973)
LWR Light-Water Reactor
NEA Nuclear Energy Agency (formerly European Nuclear Energy Agency)
NOAA (U.S.) National Oceanic and Atmospheric Administration
NRC (U.S.) Nuclear Regulatory Commission
OECD Organization for Economic Cooperation and Development
R&D Research and Development
UNEP United Nations Environment Program

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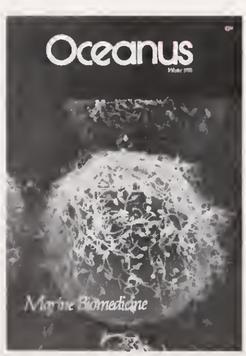

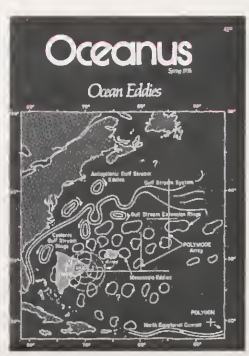

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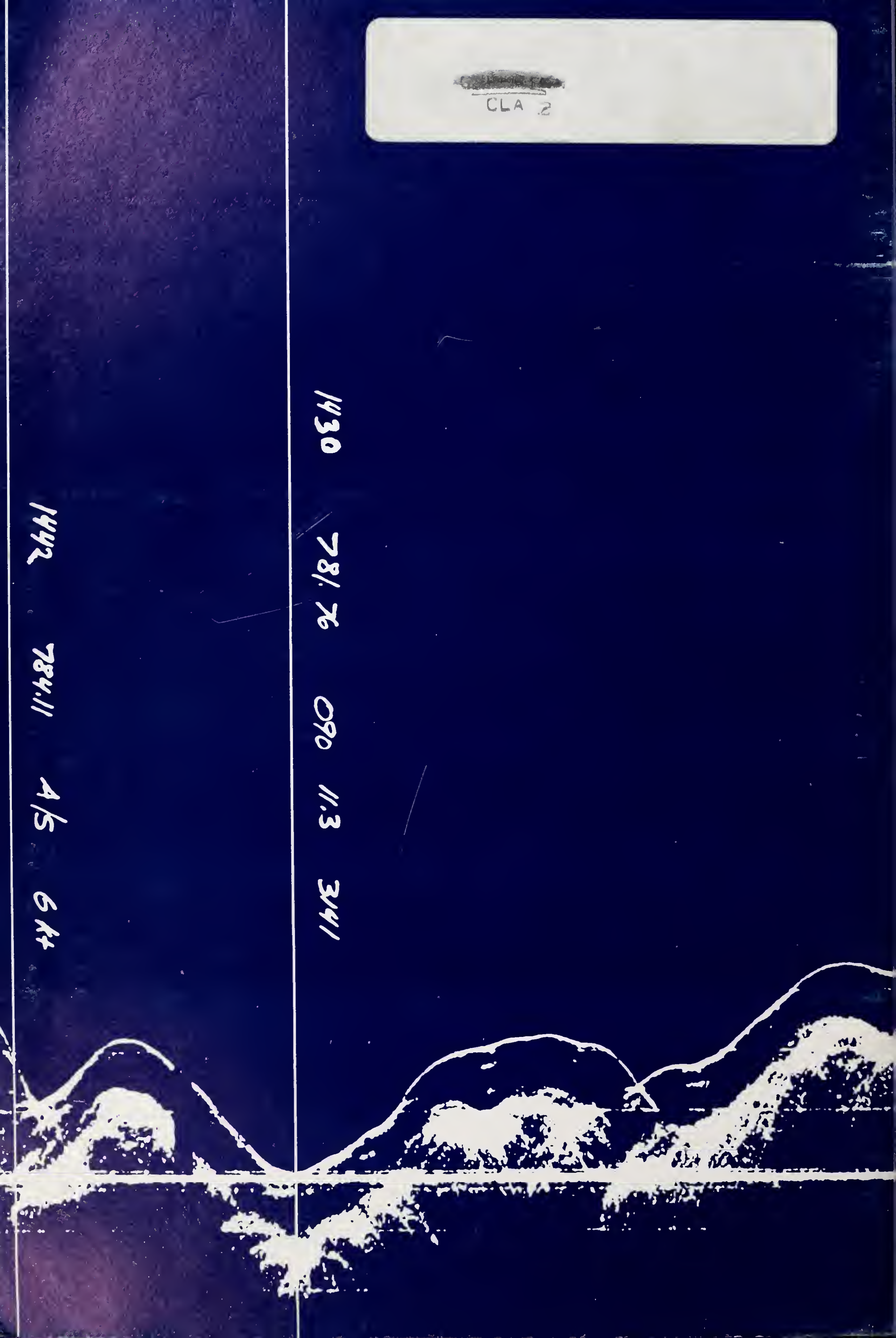
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